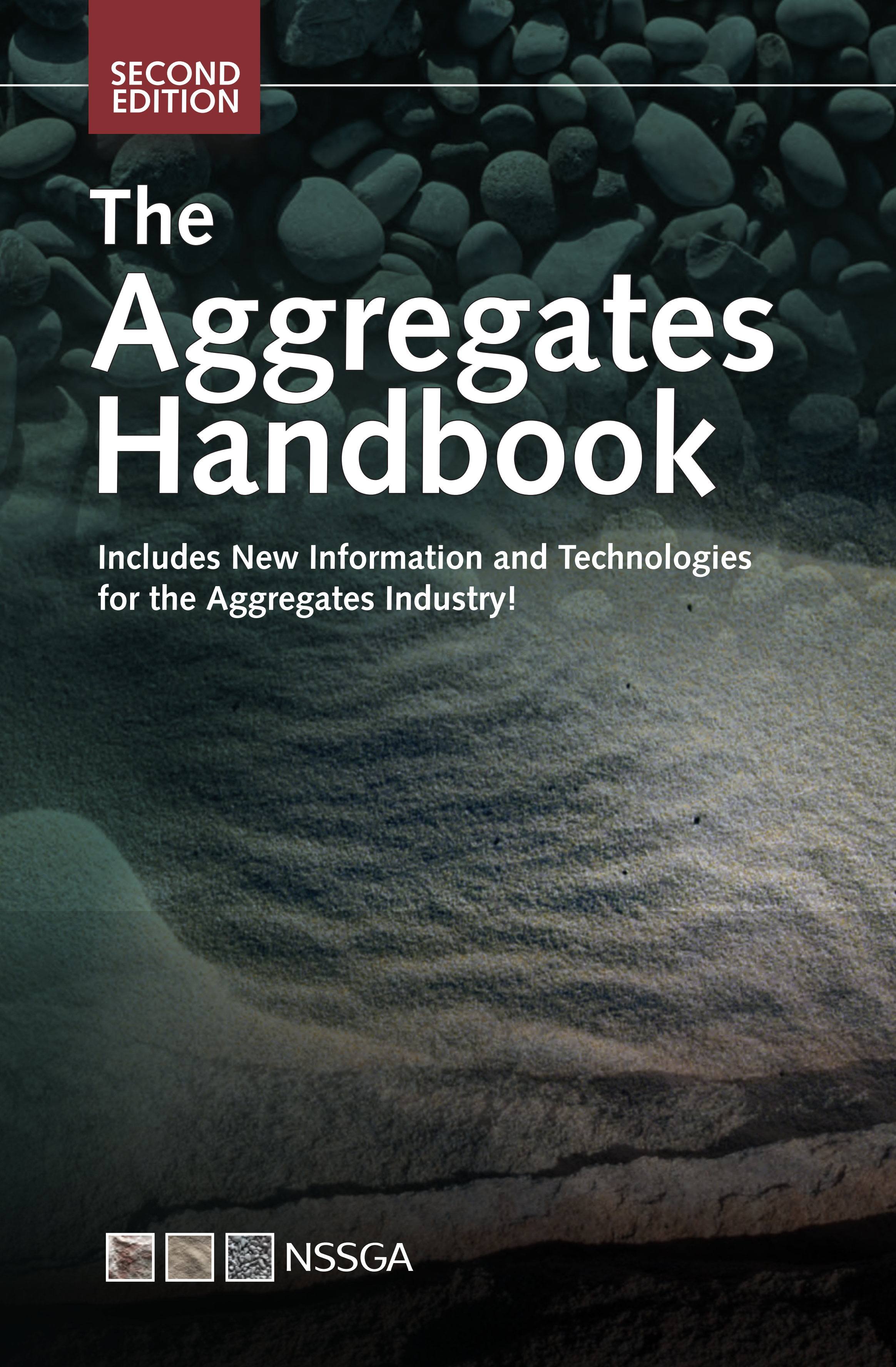

SECOND EDITION

The Aggregates Handbook

Includes New Information and Technologies for the Aggregates Industry!

NSSGA

The Aggregates Handbook

SECOND EDITION

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The National Stone, Sand and Gravel Association
Alexandria, VA

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As stated in 1991 in the original Aggregate Handbook, leaders in the aggregates industry have recognized that a comprehensive, practical and professional publication was needed to guide the growth of the industry and the proper applications of its products in engineering design, construction and other uses. This stands true today. This second edition incorporates new and updated material, including rapidly changing technologies in the aggregates industry and expanded coverage of developments in sustainability, production technology, safety, transportation, design, technology standards and industry trends.

We would like to extend our special appreciation to the Aggregate Foundation for Technology, Research and Education for their support of this project. Our thanks are extended to an outstanding group of authors, editors and contributors, representing a broad range of expertise, who have contributed so generously of their time and experience to the success of this publication.

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Foreword

The second edition of NSSGA's *Aggregates Handbook*, a collection of authoritative compilations from technical research to regulatory requirements, represents key aspects of what is required to run a successful aggregates business in the United States today.

Vast amounts of engineering, boots-on-the-ground operational and sales experience are synthesized by an expert group of association leaders and summarized as a text to educate readers inside and outside of the construction aggregates industry. This new version of the *Aggregates Handbook* is the most encyclopedic so far on how the crushed stone and construction sand and gravel industries operate in the United States from a 30,000-foot view. Readers will have a reference point to check on the latest available industry information on a variety of topics: environmental stewardship (including the environmental benefits of the planet's natural building material: stone, sand and gravel); and the aggregates industry's continuing and record-breaking improvement of safety and health statistics compared to the industries regulated by OSHA and achieving equivalent rates.

The handbook includes NSSGA's Guide to Minerals Identification and incorporates the most recent analysis of economic contributions that the aggregates sector provides this country.

While not holding itself out as the one definitive conveyor of all information on aggregates, this handbook commendably uses the insights of the industry's experts to provide elements of information directly, identify resources for inquiries and studies, and explain key concepts fundamental for the wide variety of challenges those people and companies producing aggregates must face. In its holistic and updatable educational approach, the handbook underscores strategic values if not a business imperative, to build living bridges with the communities surrounding around our industry's operations – communities that may, as a result of better understanding how rocks improve their quality of life, become if not advocates, at least accepting of the necessity for environmentally-conscientious industrial activity that provides natural materials of economic benefit, resulting in sustainable communities.

With other NSSGA conferences, seminars, digital distance learning and webinars through its AGG1 Academy, its member committees and partnering state aggregates associations, and with more public education digitally available and under development, the *Aggregates Handbook's* authors and editors provide a living reference tool for a continuum of knowledge to be exchanged.

Jennifer Joy Pinniger
President & CEO, NSSGA
November 2012

Table of Contents

Chapter 4: Environmental Compliance

Chapter 5: Sustainability

Chapter 6: Industry Health and Safety

Chapter 7: Extraction Principles

Chapter 8: Processing Plant Principles

Chapter 9: The Marketplace

Chapter 10: Product Transportation and Distribution Systems

Chapter 11: Aggregates as a Structural Product

Chapter 12: Aggregates for Structural, Geotechnical and Civil Engineering Applications

Chapter 13: Impact of Properties of Aggregates on Pavement Design and Analysis

Chapter 14: Effect of Aggregates on the Characteristics and Performance of Portland Cement Concrete

Chapter 15: Effect of Aggregates on the Characteristics and Performance of Hot Mix Asphalt

Chapter 16: Non-Construction Uses of Stone

Chapter 17: Specifications, Standards and Guidelines for Aggregates Base Course

Chapter 18: Quality Control, Sampling and Testing

Chapter 1
Introduction to the Aggregates Industry

Sam Johnson
Gus Edwards
Dave Smith

First Edition
Richard S. Huhta

1.1 Objectives of the Handbook

This handbook was developed to provide information to those who use, produce and regulate the products of the aggregates industry: crushed stone, sand and gravel.

The objective of the book is to present guidelines on the production, marketing, use and regulation of these products. However, readers are cautioned that this is not a design manual, although the handbook does contain a considerable amount of useful design information. Instead, readers should consider this a reference work; a reference manual for those whose interests include the production and use of construction aggregates.

The book was prepared for professional engineers, aggregates producers, contractors, builders and governmental agencies at all levels. Educators and engineering students also will find it a useful publication.

1.2 Organization of the Material

The handbook focuses on three majors areas of the aggregates industry.

The first major area takes the reader through the steps of locating, mining, processing and transporting aggregates material from a deposit to the marketplace. Also included in these chapters is some basic, but important, information on types of rock and their physical properties, workplace safety and health, environmental concerns and a chapter on the economic and financial characteristics of the aggregates industry.

The second major area in the handbook focuses on the users of crushed stone, sand and gravel. These chapters discuss aggregates as a structural product for base courses, drainage and erosion control; as a component in portland cement concrete and asphalt concrete mixes; and in various non-construction applications such as in the chemical and agricultural industries.

The third major area provides information on aggregates specifications and standards as well as on sampling, testing and quality control principles. The handbook also contains a complete index of key terms.

Each chapter in this book has been written by one or more individuals with special expertise in the subject gained from years of field experience and specialized training. Since the topics covered in this book are far ranging, no single person has the depth of knowledge brought forth in each chapter that these authors have accumulated. Their training and hands-on experience is what makes this handbook a truly practical and professional reference work.

Additionally, the handbook covers many of the issues faced by industry today, including how to develop the resources on one's land and bring them to a profitable sale. Also considered are zoning, permitting and developing aggregates deposits and maintaining effective community relations. This book does not solve the industry's challenges, but it does point the way to possible solutions.

In practical terms, this is the type of reference work that a state highway official can pull off the shelf for an immediate answer to a question involving the use of aggregates as a road base. Or that an engineer at a stone plant can use to help design a more productive flow of material from quarry face to stockpile.

1.3 Definitions of Terms

What do we mean when we say *aggregates* and *the aggregates industry?* As the authors use the term in this handbook, the word "aggregates" refers to any combination of crushed stone, sand, or gravel in their natural or processed state. Therefore, as used in this handbook, the "aggregates" industry means the crushed stone, sand and gravel industries as a whole. Furthermore, the term "aggregates" is divided into two sub terms: fine aggregates and coarse aggregates.

> **Fine aggregates** is considered to be any material that passes a ⅜-inch sieve and essentially all of which passes a No. 4 sieve (4.75mm) and is predominantly retained on the No. 200 sieve (75µm).[1]

> **Coarse aggregates** is generally considered to be crushed stone or gravel almost all of which is retained on a No. 4 sieve (4.75mm).[1]

We also will use the term *"construction aggregates"* and this can be defined as any combination of sand, gravel and/or crushed stone sold to or used by the construction industry.

> **Aggregates grading, or gradation**, is mentioned frequently throughout the handbook. Aggregates grading is the distribution of different particles of aggregates by size. Grading designations are often used to quickly reference the size of aggregates required for a specific application. Both AASHTO and ASTM have standard grading designations for aggregates. For example, #57 is a common aggregates size designation used to signify an aggregates with all material smaller than 1½-inches but with essentially no fines.

This handbook discusses both fine and coarse natural aggregates, both crushed and uncrushed. Processed aggregates such as slag, expanded clay-shale, or recycled material are not considered in this reference work because they are not natural products and must be handled differently. Specifically, recycled material often contains steel reinforcing (that must be removed) and large sections of cement mortar (that may pose problems when incorporated in new concrete mix designs). Slag and processed aggregates also are handled differently than the natural products and their chemical and physical properties may be different from naturally occurring materials.

Crushed stone can be composed of limestone, granite, traprock or any other hard, sound rock that is produced by blasting and then crushing. Crushed stone is produced to meet industry specifications using stationary or portable plants.

Sand and gravel is any unconsolidated mixture of fine and/or coarse aggregates material found in a natural deposit. Most sand and gravel deposits are formed by deposition in water. In fact, an examination of a geologic map of the United States shows that most deposits of sand and gravel are found along stream channels.[2]

1.4 Size of the Aggregates Industry

During the first decade of the 21st century, production of aggregates in the United States averaged three billion metric tons annually.[3] Sand and gravel accounts for roughly 40 percent of total production and most of this sand and gravel material goes into construction, specifically as aggregates for portland cement concrete and asphalt concrete mixtures. Sand and gravel also are used as road base material and as construction fill.

The remaining 60 percent of aggregates produced in the United States, are crushed stone.[4] Most of the crushed stone (69.3 percent) is limestone and dolomite, with limestone constituting the greater percentage of production. Granite products account for 13.6 percent of the total produced in the United States. Trap rock holds 6.3 percent of the market; sandstone and quartzite account for 2.9 percent; and the remaining 7.9 percent is made up of miscellaneous rock such as slate, marl and shale.[4]

The vast majority of the crushed stone produced in the United States is used as construction aggregates, primarily in highway and road construction as road base or in portland cement concrete and asphalt concrete as an essential ingredient.[4] The remaining crushed stone is used in the chemical and metallurgical industries for agricultural purposes and for a variety of other applications such as railroad ballast, riprap, jetty stone, flux stone and filter stone.

1.5 Economic Importance

Aggregates are used extensively in the vast majority of construction projects, making the aggregates industry a major contributor to the physical well-being of the United States. A major highway cannot be built without fine and coarse aggregates. Neither can a big shopping center, an airport, locks along the Mississippi River or dams in the West. Railroads need stone as ballast to provide safe travel for their passengers, and freight and harbors need stone jetties and breakwaters for protection against wave action. High-quality dolomitic limestone also finds use in the chemical, steel and lime industries.

Average annual sales of aggregates during the first decade of the 21st century exceed $21 billion in the United States.[3, 4.] The aggregates industry typically employs over 100,000 persons in the United States, according to U.S. Census Bureau statistics. These people work in all fifty states and bring home earnings of $4.6 billion annually.

The South leads the United States in production of crushed stone with 48 percent of total production originating in this area. The Midwest is second with 26 percent, followed by the Northeast with almost 14 percent.[4] The Mountain and Pacific areas produced 12 percent.[4]

Of all states, Texas has been the predominant leader in the production of crushed stone followed by Pennsylvania, Missouri, Florida, Illinois, Georgia, North Carolina, Virginia, Ohio and Indiana. The combined production of these top 10 states represents more than half of the crushed stone produced nationally.[4]

Looking at individual operations, there are 13 crushed stone plants in the United States capable of producing over 5 million metric tons per year (tpy).[7] Conversely, there are 12 sand and gravel operations in the United States that can manufacture more than 2.5 million metric tpy.[12]

In 2008, California has led states producing sand and gravel closely followed by Texas, Arizona, Michigan, Washington, Utah, Colorado, Wisconsin, Minnesota and New York.[3] Regionally, the West produced more construction sand and gravel than any other region. The South was second and the Midwest was third.[3]

Current, detailed statistics are available at *http://minerals.er.usgs.gov/minerals/pubs/commodity* for "Sand and Gravel, Construction" and for "Crushed Stone."

1.6 Historical Perspective

In the late 1800s, the mining of crushed stone, sand and gravel was labor intensive, as was virtually all manufacturing and construction activity throughout the United States. In mining operations, men with sledge hammers and shovels used their muscles to work the pits and quarries scattered around the country, as illustrated in Figure 1.1.

Today, the industry is vastly different. It has evolved from being labor intensive to capital intensive and an industry where manpower directs and controls operations, not performs menial tasks. Today, the industry uses computer-age technology and modern business techniques to make a product that must meet specifications having tight tolerances on gradation and other physical properties. Today, it is possible to see a modern aggregates plant running on full automatic control with only one or two persons checking performance.

Gone are the sledge hammers, the picks and the mules. Gone, too, are the quarry carts laden with stone. Instead, rubber-tired, front-end loaders now dig and load aggregates into huge haul trucks. The trucks then typically discharge into a crusher that flows to conveyor belts capable of moving material quickly and efficiently to and through an intricately designed processing plant.

Shortly before the turn of the twentieth century, little was known about the quantity and value of aggregates produced in the United States. Then, in 1882 the U.S. Geological Survey began publishing *Mineral Resources of the United States*. The first chapter on stone was added in 1889 and the first report on sand and gravel appeared in the 1905 edition.[9] Initially, aggregates production was given as dollar value of product sold, not as tons produced. Currently, aggregates production is given as both tons produced and dollar value of product sold or used.

In 1900, the dollar value of crushed stone produced and sold in the United States was reported at $24 million.[10] Fifty years later, the industry produced 325 million metric tons of crushed stone with a value of about $422 million.[11] In 2006, crushed stone producers set the current production record: 1.78 billion metric tons with a reported value of $14.2 billion.[4]

Sand and gravel production in 1905 was 25 million short tons valued at about $10 million.[12] In 1950, at the halfway mark of the century, the industry mined 370 million metric tons valued at $295 million.[13] In 2006, 1.33 billion metric tons of sand and gravel were produced with a value of $8.6 billion, also the current production record for sand and gravel.[3]

Photo courtesy of Martin Marietta Corp.

Figure 1.1 An early 1900 quarry scene at the Neverson Quarry in eastern North Carolina.

Pictures of early-1900s aggregates operations show men with big, brimmed hats and long, dark coats working a quarry or a gravel deposit. In their hands or resting at their sides are sledge hammers or picks. Nearby stands a cart, ready to receive aggregates and in front of the cart is a team of docile-looking mules or horses. Aggregates material was hauled from quarry to plant and from plant to customer by these teams of mules or horses. Later came steam-powered tractors rolling on big iron wheels.

A Buffalo Pitts Co. advertisement in the May 1903 issue of *Rock Products* magazine pictured a steam tractor pulling two cars. The headline and the copy shouted out the advantages of replacing the horse:

> ***"Cheaper Than Horses"***
>
> *"For hauling crushed stone, our engines are far cheaper than horses and are rapidly displacing them wherever the work is sufficient so that an engine can be used to advantage. They ascend heavy grades, work 24 hours a day, never tire, sicken or die and eat only when working."*

Eventually, company-owned steam locomotives and quarry cars replaced both the steam tractor and the mule-powered cart in quarry operations (see Figure 1.2). By 1905, advertisements for steam locomotives were appearing regularly in the trade press[14] and their use in stone operations extended well into the 1930s. But in that decade, gasoline- and diesel-powered locomotives began to replace the steam engine. Manufacturers of internal combustion locomotives claimed that their engines had stronger draw power than steam models.

Crawler dozers with crawler-equipped dump trailers also entered the scene in the 1930s and were used to move stone from the quarry to the processing plant. Similarly, small haul trucks began to operate in various pits and quarries around the country and some plants used the type of dumpsters commonly seen on construction sites today for hauling concrete and moving their aggregates from place to place as illustrated in Figure 1.3.

By 1947, locomotives still were found working in stone operations and a buyers' guide published in the January 1947 issue of an industry trade magazine listed manufacturers of 10 different types of locomotives (steam, battery-operated, electric, oil, kerosene, etc.).[15] However, haul trucks were seen more and more frequently as industry producers found them to be more mobile and probably cheaper to operate than locomotives.

Early advertisements in trade journals featured names of equipment manufacturers that are still familiar. Between 1902 and 1908, advertisements appeared in trade magazines from such currently well-known companies as Ingersoll-Rand Co., The W.S. Tyler Co., Jeffery Mfg. Co. and Sturtevant Mill Co. Advertisements also were placed by many companies that have passed into history, such as Ohio Steel Wheelbarrow Co., Chicago Belting Co., Davenport Locomotive Works, Good Roads Machinery Corp., The Ohio Cooperage Co., McKiernan Drill and the Independent Powder Co. of Missouri.

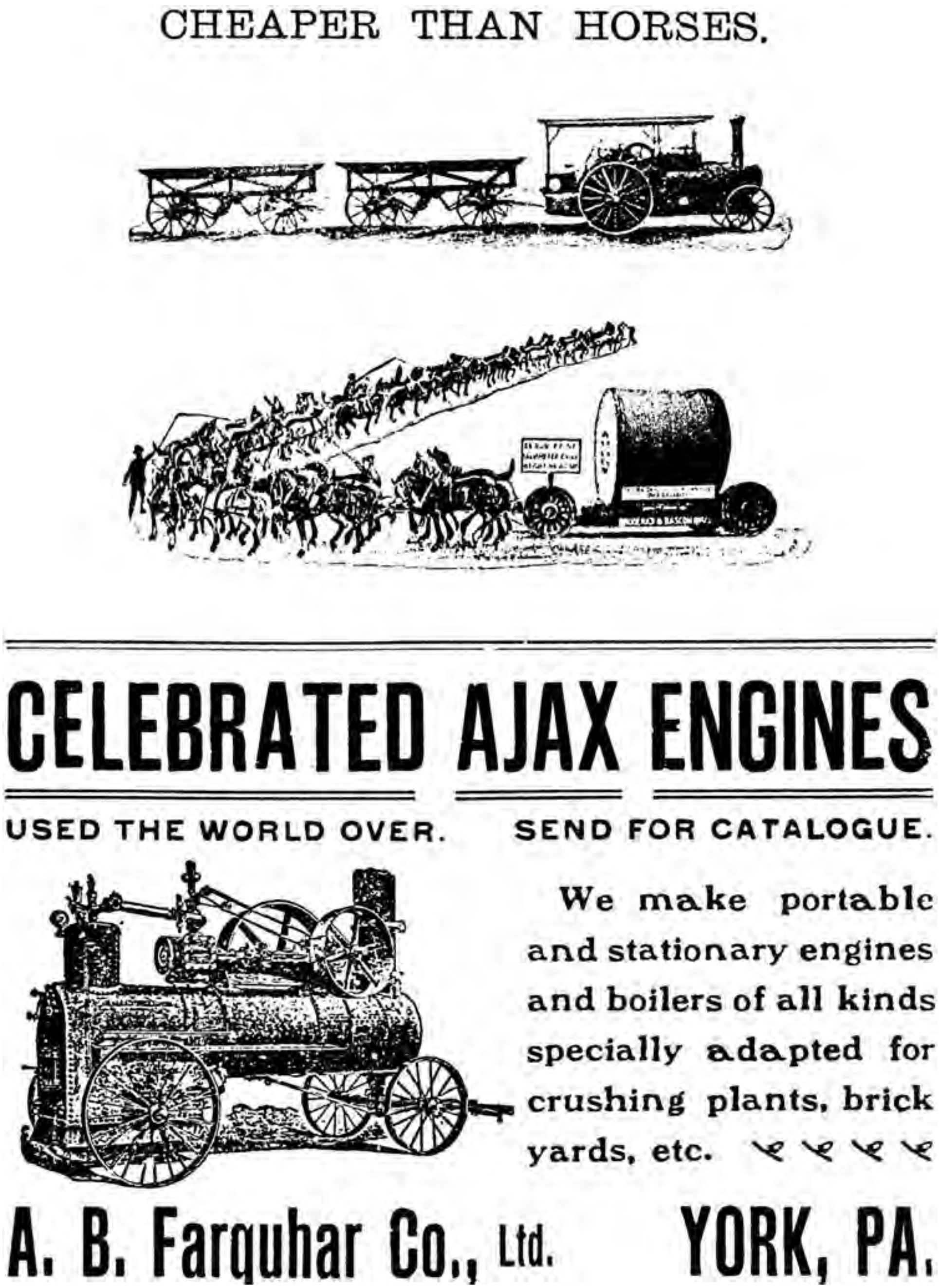

Photo courtesy of Rock Products magainze

Figure 1.2 By about 1903, steam-powered tractors were replacing the horse and mule as motive power in aggregates pits and quarries.

Photo courtesy of International-Hough Division

Figure 1.3 Early front-end loaders were clumsy looking machines, but they got the job done faster than previous methods. This picture was taken in the 1920s.

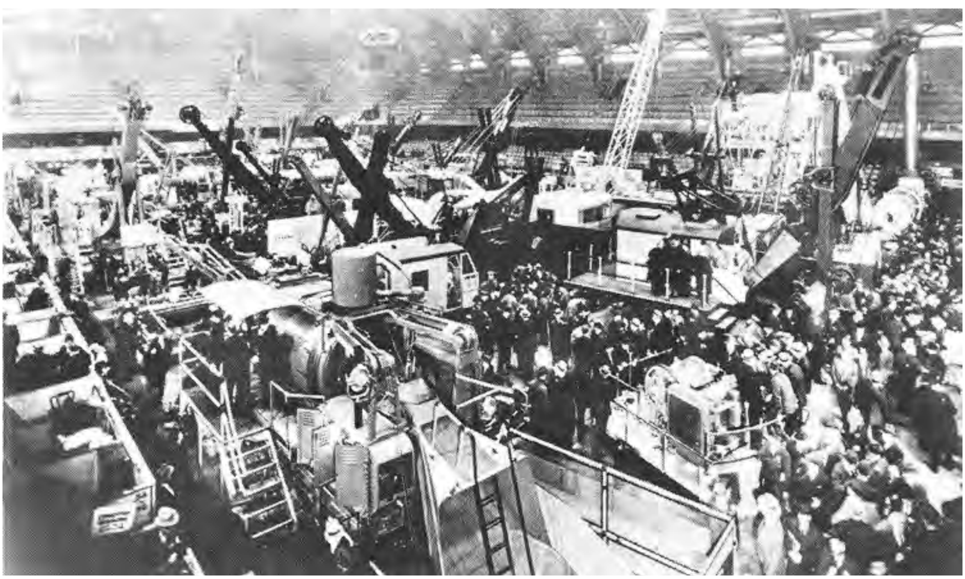

Photo courtesy of Rock Products magazine

Figure 1.4 The 1940 Road Show, displaying numerous pieces of mechanical equipment—including several steam shovels and at least one steam locomotive—was of interest to all segments of the construction industry.

Early in its history, the aggregates industry quickly developed a reputation for inventiveness as men sought a means of relieving the strain on their backs and muscles. That bent toward innovation stayed with the industry even as it became more mechanized. But, inventive as the aggregates industry was, the business really did not begin to develop as it is today until the late 1940s. That is when sophisticated processing equipment and big, highly productive quarry machines began to find their way into this marketplace. By the 1940s, mechanical equipment of interest to all segments of the construction industry was being displayed in the Road Show, as illustrated in Figure 1.4.

As productivity increased, so too did quality control. Product quality and the desire to provide good service always have been the trademarks of reputable manufacturers and the aggregates industry is no exception. The industry has been fortunate to have several national associations help achieve its goals. The National Crushed Stone Association was founded in 1918 in Columbus, Ohio, by a group of concerned quarry operators. It would later become known simply as the National Stone Association. Two years prior to the formation of the National Crushed Stone Association, in 1916, its counterpart in the sand and gravel industry formed the National Sand and Gravel Association, which later became known as the National Aggregates Association. But even before this, on May 19, 1903, the National Quarry Owners Association was formed in Chicago. Elected president was D. McL. McKay of Perry-Mathews-Buskirk Stone Co., in Chicago, Ill. The membership fee was $10 and annual dues were another $10.

The successors to these early organizations, the National Stone Association and the National Aggregates Association, were leaders on the educational and legislative fronts. They helped upgrade the training and education of industry personnel and provided the public with a greater understanding of aggregates mining and production for over 80 years. Then, in 2000, the National Stone Association and the National Aggregates Association joined forces to become one united voice for the aggregates industry: the National Stone, Sand and Gravel Association, NSSGA.

Today the NSSGA continues its lead role in promoting the technical, economic, social and regulatory environments in which the aggregates industry can compete and flourish.

1.7 Trends

Like all things dynamic, the aggregates industry continues to grow and change to meet the needs of its customers and the demands of modern society. The industry has had—and will continue to have—its challenges, but the smart, aggressive producers see these as opportunities to improve their workplaces and provide a competitive advantage.

Looking at this industry's future, several opportunities are on the horizon or lurking nearby that will both benefit and challenge those who mine and produce aggregates today. Among these opportunities are greater transportation distances, higher energy costs and integration.

Other trends (or realities) include the following:

Computer-Controlled Plants: Computer-controlled processing plants have been the standard for many years. Computers increase plant efficiency and control essentially all aggregates-processing equipment, from crushers, conveyors and screens to automated sampling devices. By monitoring and regulating drive-motor amperage, computers constantly adjust the flow of material through the plant and ensure peak performance. Sonic sensors in storage bins also monitor material flow and ensure constant feed to crushers. Today, many plants operate with fewer but more highly trained individuals. Processing plants can be set to run without any plant personnel at the site. In case of a problem, the plant automatically shuts down and notifies the plant manager by sending an alert to their cell phone. Computers also aid in quality control. Today, automatic belt samplers are installed in many locations and can discharge samples directly to an automatic sieving device for gradation analysis. Optical devices are currently under development that grade aggregates in real time without ever removing a sample from the production flow. Undoubtedly, there will continue to be more developments in the area of computer-controlled operations.

Improved Quarry Operations: The second trend involves improving quarry operations. One might think that quarry operations already have been refined as much as possible. After all, quarrying consists of simply drilling and blasting rock and then moving it to the processing plant. How can that be improved?

The entire quarry process recently has been altered by the development of highly mobile crushing plants that move into the quarry to crush and screen the material at its source. These mobile crushers are actually processing plants mounted on crawler tracks, rubber tires or walking pads that can carry them close to the quarry wall as loaders muck material from the working face. Some of these plants can process up to 5,000 tons per hour.

Mobile, in-pit crushers are not for all quarry operations. The units are big and expensive, and quarry conditions have to be just right for the unit to be profitable. However, those producers—and so far there are only a few—who are moving to mobile, in-pit operations are doing so to eliminate truck haulage and produce more material faster and cheaper than any other existing technique.

Generally, producers who have installed mobile crushing plants tie them into a string of movable conveyors that carry the material from the quarry to the main processing plant where the stone is further sized to specification.

Manufactured Sand: The third trend involves better use of manufactured sand in concrete. In some parts of the country natural, coarse sand is in short supply. However, the crushed stone industry can help fill this void with a product known as manufactured sand. Fine aggregates is produced by crushing larger sized aggregates. These fines can be further processed and used as a viable alternative to natural sand in concrete. [Recent research supported by the Aggregates Foundation for Technology, Research and Education (AFTRE) and completed by the International Center for Aggregates Research (ICAR) continues to progress the knowledge base of manufactured sand for use in concrete. Research findings, such as improved concrete performance using manufactured sand with higher fines content, are discussed in later chapters in this handbook and more information can be found on the AFTRE webpage (www.nssga.org/aftre/index.cfm).

Improved Blasting Techniques: The fourth trend is a movement toward improved blasting techniques and procedures to prevent fly rock (flying rock fragments from a quarry blast) and vibration damage to nearby buildings. Aggregates producers today consider it a normal part of the blasting operation to install seismic equipment near any vulnerable building. This equipment is monitored regularly and provides both resident and quarry operator with an accepted and authoritative report on any quarry-generated sound or vibration.

Damage from fly rock is no longer the threat it once was. Improved loading patterns, careful spacing of blast holes, improved explosives and the retention of professional explosive experts have virtually eliminated blasting-related fly rock.

Public Awareness: There is a continuing trend by aggregates operators to be more aware of and sensitive to the needs and concerns of the general public. Most aggregates producers today are extremely concerned about public opinion. Many have worked hard to win the trust and support of their residential and commercial neighbors and the files of those producers who have been good corporate citizens are filled with the positive results of carefully developed community relations programs. For example, plant beautification efforts that improve an operation's "street appeal" often begin with simple front-gate landscaping and colorful flower beds. The message to observers and passersby is clear: "We're your neighbors—we care how you feel about us."

Noise, dust and water pollution controls are areas where industry has invested millions of dollars with great success over the last 20 years. Plant operators continually seek new ways to reduce the real or perceived impact of their operations. In many communities, plant operators have won the respect of their neighbors for minimizing the impact of their plant or equipment on the environment. Some of the techniques are simple and inexpensive. Other are more elaborate and, generally, more costly.

Occupational Safety and Health: Hardly any longer a novelty, more and more operators today proactively manage workplace conditions and activities to ensure the safety and health of their employees in order to meet or exceed regulatory requirements. Modern operators integrate the following safety and health programs and processes directly into the fabric of their business: site acquisition, mining plan development, personnel recruiting and training, plant design and engineering, operations and maintenance and human resource functions such as promotions, compensation, corporate awards and community recognition. Developing and continuously improving an integrated safety management system, these operators long ago abandoned a reactive reliance on (and frequently adversarial relationship with) federal and state regulators to tell them what to do. In the process, many modern operators discovered that their integrated safety management systems could spell the difference between a profitable operation and one that goes out of business.

Construction verses Maintenance: With an ever-growing infrastructure and limited funds for new construction, recent trends in highway spending have focused on maintenance rather that new construction. From an aggregates industry standpoint, maintenance procedures require a much different product mix than new construction. Maintenance operations tend to focus on either asphalt or thin concrete overlays, both requiring a much smaller size and often cleaner aggregates. Producing smaller, cleaner aggregates requires additional crushing, screening and washing which generates, in many cases, excessive fine aggregates. In short, maintenance with little new construction creates a product imbalance for much of the industry. Researchers and practitioners in the industry are constantly looking for new markets to utilize fine aggregates.

Recycling Quarries and Pits: Of all the trends impacting the aggregates industry, the most dramatic is the trend toward the recycling of mined-out pits and quarries to useful and profitable second uses. No other single development carried out by the aggregates industry in the past 100 years has brought it greater acclaim.

Today, mined-out pits and quarries are being used as sites for both dramatic new projects and for mundane but highly useful applications. For example, in Indianapolis, Ind. and Rochester, N.Y., developers have filled mined-out sites with water and built luxury condominiums and townhouses around the perimeter.

In Virginia, owners of a working quarry are converting a major portion of a mined-out section into a 16¬acre shopping center. Quarry owners and shopping center developers have worked hand-in-hand to reduce quarry noise and dust to a level that businesses in the shopping center have found acceptable. This quarry will be separated from the shopping center by an attractively planted earth berm. In Penfield, N.Y. and Crystal River, Fla., far-sighted land planners have turned old limestone quarries into innovative settings for golf courses.

Reclamation is now a booming business and nobody is happier to see worked-out mining sites turned into viable, profitable second uses than the people who mined the sand and stone in the first place.

Emerging Challenges: There also are developments emerging that pose serious problems for the industry that dramatically may affect the way the industry will be able to conduct business in the future. One great difficulty is developing new sites or building new plants. Public opposition to a proposal to enlarge a site or develop a new deposit sometimes occurs at zoning hearings. More often than not, this opposition is created by a few extremists who raise the specter of dust, danger and deterioration of property values whenever an aggregates producer seeks permission to expand or develop a new site.

Greater Environmental, Safety and Health Awareness: Reclaiming old pits and quarries are only one example of the aggregates industry's efforts to improve the environment. Aggregates producers are (and have been) working hard with federal, state and local environmental agencies to designate wetlands and preserve those in danger of being damaged; reduce dust and other emissions from their operations; eliminate or control workplace safety and health hazards, reprocess waste water until it is clean enough to be released beyond the confines of their operations; control or eliminate excessive noise from their machines and equipment; and, in general, work to provide a clean, healthy environment for this and future generation of Americans.

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Chapter 2
Basic Properties of Aggregates

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2.1 Introduction

Scope

This chapter discusses the basic physical, chemical and mechanical properties of aggregates. Pertinent properties are defined and the significance of each property is discussed briefly. Properties of specific aggregates types and commonly used methods for testing aggregates to determine selected properties are summarized.

Role of Aggregates in Construction

Aggregates plays a critical role in the design and construction of the nation's infrastructure. The major component in hot mix asphalt and portland cement concrete is aggregates. Furthermore, aggregates are used almost exclusively as a base material for pavements and other building applications.

Properties: The properties of aggregates and aggregates-binder mixtures are very important to the life of the system in which they are used. Examples are numerous failures traceable directly to improper aggregates selection and use. Improper design of aggregates base courses in many instances has led to premature breakup of pavements, often due to poor drainage and frost action. Use of nondurable aggregates has caused rapid deterioration of portland cement concrete under severe weathering conditions, including freezing and thawing. Use of improper aggregates in asphalt concrete construction has led to the binder being stripped away from aggregates particles, resulting in rapid pavement deterioration. Clearly, proper aggregates selection is necessary for attaining the desired performance.

Quality: Producers of aggregates for use in construction must give careful attention to quality control of the aggregates. The aggregates must possess properties that:

- Permit the construction to fulfill its intended function for the desired design life. For example, a pavement must function as the support system for the applied traffic loading by providing the support and surface conditions necessary for the *safe, economical* and *comfortable* operation of vehicles on the pavement.
- Allow the aggregates to be handled and manipulated satisfactorily during construction.

Even though aggregates may have properties that allow the system in which they are used to perform satisfactorily, they must also possess certain characteristics that are dictated by construction procedures. The aggregates must possess properties that allow them to be handled satisfactorily during:

- Shipment and storage;
- Mixing of the aggregates with binder or other aggregates;

- Placement of the mixture; and
- Compaction and/or curing of the mixture.

Binder: The aggregates is not the only physical element that influences the ability of a system to fulfill its intended functions. The characteristics of binders such as asphalt and portland cement and the interaction between the binder and aggregates also have a significant influence on the performance of the system. Only properties of the aggregates that influence system behavior are defined and discussed in this chapter.

Aggregates Use: The actual levels of all needed properties are influenced by how the aggregates are used in the system. Many properties of the aggregates, such as strength, are required at some level regardless of the aggregates use. Aggregates used in asphalt concrete do not necessarily need to have the same properties as those used in portland cement concrete. Different aggregates properties frequently are required for different end-uses. For example, an aggregates source that performs well in hot mix asphalt may be chemically reactive with portland cement making its use limited in concrete.

2.2 Functions of a Construction System

Generalized functions of various construction systems in which aggregates play a major role are as follows:

1. Adequate internal strength and stability to distribute surface pressures and to prevent extensive surface deflection;
2. Resistance to deteriorating effects of weather and chemical actions;
3. Resistance to deteriorating effects produced by applied static or dynamic loads;
4. Resistance to the effects of internal forces, such as expansion, contraction and warping and curling;
5. Aggregates-binder compatibility; and
6. Retention of acceptable standards of performance when exposed to traffic as in a surface course. Consideration must be given to the following surface properties:

    - Skid resistance
    - Surface roughness
    - Glare and light reflection
    - Loose material
    - Tire wear
    - Rolling resistance
    - Noise level
    - Electrostatic properties
    - Appearance

The properties that aggregates must possess so that the system fulfills its function are summarized in Table 2.1. The relative importance of a specific property also is given in this table for various construction applications.

Table 2.1 Aggregates Properties for Specific Uses to Meet Functions of the System[1]

		Relative Importance of Property		
Function	**Aggregates Property**	**PCC**	**Asph. Conc.**	**Base**
1. Adequate internal strength & stability to distribute Serface pressures and to prevent extensive surface deflections	1. Mass stability	NA	I	I
	2. Particle strength	I	I	I
	3. Particle stiffness	I	I	I
	4. Particle surface texture	I	I	I
	5. Particle shape	I	I	I
	6. Grading	I	I	I
	7. Maximum particle size	I	I	I
2. Resistance to deteriorating effects of weather and chemical actions	1. Resistance to chemicals, such as salts	I	U	NA
	2. Solubility	I	I	I
	3. Staking	I	I	I
	4. Resistance to wetting/drying	I	U	I
	5. Resistance to freezing/thawing	I	U	I
	6. Pore structure	I	I	I
3. Resistance to deteriorating effects produced by applied loads	1. Resistance to degradation	I	I	I
4. Resistance to the effects of internal forces, such as expansion, contraction, warping and curling	1. Volume change—thermal	I	N	N
	2. Volume change—wetting and drying	I	N	N
	3. Pore structure	I	N	N
	4. Thermal conductivity	I	N	U
5. Aggregate and binder compatibility	1. Chemical compounds reactivity	I	I	N
	2. Organic material reactivity	I	N	N
	3. Coatings	I	I	N
	4. Thermal volume stability	I	N	N
	5. Base exchange	I	I	I
	6. Surface charges	N	I	N
	7. Pore structure	U	N	N

		Relative Importance of Property		
Function	**Aggregates Property**	**PCC**	**Asph. Conc.**	**Base**
6. Retention of a surface that will assure acceptable standards of performance. To have this characteristic, consider the following serface properties:				
a. Skid resistance	1. Particle shape	I	I	NA
	2. Particle surface texture	I	I	NA
	3. Maximum particle size	N	I	NA
	4. Particle strength	I	I	NA
	5. Wear resistance	I	I	NA
	6. Particle shape of abraded fragm.	I	I	NA
	7. Pore structure	I	I	NA
b. Surface roughness	1. Maximum particle size	I	I	NA
	2. Grading	I	I	NA
c. Glare and light reflection	1. Reflection	I	I	NA
	2. Glare	I	I	NA
d. Loose material	1. Resist. To degradation	I	I	NA
	2. Specific gravity	N	N	NA
e. Tire wear f. Rolling resistance	1. Particle shape	I	I	NA
	2. Particle surface texture	I	I	NA
	3. Maximum particle size	I	I	NA
	1. Maximum particle size	U	I	NA
	2. Particle shape	I	I	NA
g. Noise level	1. Maximum particle size	U	I	NA
h. Electrostatic properties	1. Electrical conductivity	U	I	NA
i. Appearance	1. Particle color	N	N	NA
	2. Oxidation and hydration reactivity (stains and popouts)	I	N	NA
7. Retention of prop. During the construction process that supports all other functions of the system	1. Maximum particle size	I	I	I
	2. Resistance to degradation	I	I	I
	3. Integrity during heating	N	I	N

Note: I = Important; N = Not important; U = Importance unknown; NA = Not applicable; PCC = portland cement concrete; Asph Conc. = bituminous or asphalt concrete; Base = Unbound aggregates base

2.3 Definition and Discussion of Aggregates Properties

Definition of Aggregates Properties

A property is a quality that is indicative of a specific characteristic of a material. A number of properties exist that identify the behavior of a material under different conditions. For instance, there are *elastic, magnetic, chemical, physical* and *mechanical* properties, as well as others. A property may or may not be identified by a numerical value, but preferably it can be. Aggregates properties can be grouped into three categories:

- Physical Properties
- Chemical Properties
- Mechanical Properties

For a given construction application, only some of the defined properties are pertinent. As a result, aggregates do not necessarily have to exhibit a high quality in every property. Important properties and the quality needed in aggregates depend on the specific application, the type of binder used, the performance desired and economics. Requirements for pertinent properties and consistency of these properties are established by the specifying agency for each particular construction application.

A number of the basic aggregates properties considered in this chapter cannot be measured quantitatively. Others can be measured, but not precisely. Standard test methods for determining some of the most commonly measured properties and the significance, limitations and problems associated with these tests, are described in detail in Section 2.5. ASTM and AASHTO Standards for aggregates are listed in the Appendix to this chapter.

Physical Properties

The physical properties of a material identify or describe it in terms of the fundamental dimensions of length, mass and time. Physical properties that are important for aggregates used in construction are discussed below.

Particle Angularity and Shape: *Angularity* is a measure of the aggregates particle's degree of crushing. For example, crushed granite or limestone aggregates are considered angular whereas uncrushed gravel would be considered rounded. *Particle shape* is the shape of the individual aggregates particles. Aggregates particle shapes are described as being cubical, flat, elongated, or flat and elongated. In asphalt concrete mixtures and unbound aggregates base material, angular, cubical particles are desired to develop aggregates interlock, which increases the shear strength of the mixture. Aggregates of any shape, however, can be used in portland cement concrete to obtain high strength, provided the water/cement ratio of the mixture is adjusted. Angular aggregates particles are also desirable at the surface of a pavement to promote high skid resistance. Such particles, however, may increase tire wear and the rolling resistance of the surface.

Maximum and Nominal Maximum Particle Size: The terms maximum and nominal maximum particle size are used to give a general description of the size of an aggregates product. In terms of the gradation specifications, *maximum particle size* is defined by ASTM C 125 as the smallest sieve opening through which the entire amount of aggregates is required to pass. The nominal maximum particle size is defined as the smallest sieve opening through which the entire amount of aggregates is permitted to pass. If the aggregates size range is stated in terms of two sieves, such as ¾-inch to ½-inch, the maximum particle size is the larger of the two sizes given.

Maximum and nominal maximum sizes are defined differently by the hot mix asphalt industry. When referring to hot mix asphalt, nominal maximum size is one sieve size larger than the first sieve to retain more than 10 percent. Maximum size is one size larger than the nominal maximum size.

Mixtures for most construction applications can be prepared satisfactorily using aggregates that have a wide range of maximum aggregates sizes. Some desirable characteristics of the mixture are improved by using large-size aggregates. For instance, the strength of the mixture generally is increased when aggregates larger than ½-inch are present. Conversely, large-size aggregates at the surface increase the noise generated, increase tire wear and produce greater rolling resistance. During lay down, large-size aggregates can cause mixture segregation to take place and during finishing it can produce a harsh mixture that is difficult to handle and finish smoothly.

Particle Surface Texture: *Particle surface texture* is the degree of roughness or irregularity of the surface of an aggregates particle.

Although smooth-surface-textured aggregates can be used satisfactorily for some construction applications, rough-surface-textured aggregates usually are preferred. The strength of an asphalt concrete mixture and of an unbound aggregates base is increased when rough aggregates are used. Also, rough-surface-textured aggregates are useful in surface course mixtures to help provide high friction levels between rubber tires and the pavement surface. When the rough surface texture of aggregates is removed through wear by tires, the friction is decreased.

Aggregates with any texture, varying from smooth to rough, can be used in most normal portland cement concrete provided the mixture is properly proportioned. A rough texture, however, can improve the bond strength between the aggregates and the paste which is desirable for mixes requiring high flexural or compressive strength.[2]

In hot mix asphalt, smooth textured aggregates are relatively easy to mix and coat. However, the smooth texture often can lead to durability and stability problems. The bond between smooth textured aggregates and asphalt binder can be relatively weak, which may lead to stripping of the binder away from the aggregates. Furthermore, the smooth textured particles may result in a mix with low internal friction, which could lead to low stability, rutting and other problems.

Pore Structure: *Pore structure* is the size, volume and shape of the void spaces within aggregates particle. Pores can be either *impermeable* (isolated, enclosed cavities) or *permeable* (interconnected and extending to the surface of the particle). Pores may be continuous and interconnected so that large permeable voids form large passageways through the aggregates; or they may be dispersed, small-volume voids.

Large volumes of permeable pores normally are not desirable in conventional aggregates for most construction applications. When an aggregates are subjected to repeated cycles of freezing/thawing and/or wetting/drying, deterioration of the aggregates may result. If the aggregates, when subjected to these conditions, absorb large volumes of water or salt solutions into the pores, deterioration may be accelerated. A large volume of permeable pores also increases the absorption of binder. When excess binder is required to fill these large voids, the cost of the paving mixture is increased. It is desirable that the pores not only have a low volume, but also are well dispersed and discontinuous.

For some applications, advantages exist in having pores in the surface of the aggregates. Normally, surface pores contribute to a rough surface texture which consequently increases surface friction. Also, water that is absorbed by aggregates used in portland cement concrete is available for release at a later time with a resulting improvement in the curing conditions. While it is recognized that these advantages exist, aggregates need not contain permeable pores, provided a rough surface texture is present.

Absorption: *Absorption* is the penetration of liquid into aggregates particles with a resulting increase in particle weight.

Most aggregates particles are capable of absorbing water or other liquids. Absorption by various types of aggregates ranges from virtually zero to over 30 percent of the dry aggregates weight. If construction aggregates are highly absorptive, the binder requirement and/or mixing water requirement for desired the mixture characteristics is increased. The economics of the construction is adversely affected if more binder is required. Aggregates having less than 1 percent absorption minimizes binder requirements and are generally preferred for most construction applications provided it is readily available and economical.

Porosity: *Porosity* is the percentage of the total volume of an aggregates particle occupied by pore spaces.

Porosity affects the strength and elastic characteristics of aggregates particles and may affect their absorption, permeability and durability characteristics. Igneous and metamorphic rocks have very low porosity. Most sedimentary rocks have a higher degree of porosity. Some sedimentary rocks have pore spaces occupying as much as 50 percent to 75 percent of the total volume. In general, lower porosity aggregates particles are preferred for most construction uses. If only high porosity aggregates is available, aggregates having impermeable, non-interconnected pore spaces are generally superior to aggregates having permeable pore spaces.

Permeability: *Permeability* is the capacity of an aggregates particle, or a group of particles, to transmit a fluid.

Most igneous, metamorphic and fine-textured sedimentary rocks are relatively impermeable to water. However, certain rocks have a high permeability and may be undesirable for use in some construction applications. Permeability must be distinguished from porosity. Aggregates particles may have a high porosity but, because the openings are not connected or because the openings are of small size, they are impermeable to the flow of water.

The overall permeability of a group of particles is determined primarily by the grading and density of the mixture of aggregates particles. The coefficient of permeability of unbound aggregates materials used in construction ranges from 0.001 to as much as 100,000 feet/day depending on grading and density.

Specific Gravity: *Specific gravity*, also referred to as *relative density*, is the ratio of the mass of a given volume of aggregates to the mass of an equal volume of water.

For most applications, specific gravity itself is not a critical property. Aggregates with a specific gravity of 3.00 are not necessarily better than those with a specific gravity of 2.55. However, it is important to determine accurately the specific gravity since it is used in designing concrete and hot mix asphalt mixtures. If an inaccurate specific gravity is used during mixture design, the mixture properties may not meet specification requirements. Once a mixture is designed, it is then critical to maintain a consistent specific gravity.

Specific gravity also can be used to detect deleterious particles in an aggregates product. Deleterious particles such as coal, lignite, wood and others that are sometimes present in aggregates often have a lower specific gravity. Hence, separation of deleterious particles frequently can be accomplished utilizing this difference in specific gravity.

Some aggregates applications, such as erosion control and railroad ballast, require high particle weight per unit volume (i.e., high specific gravity). A high specific gravity provides stability to the system without requiring an increased layer thickness or increased track cross section.

Particle Grading: *Particle grading* or *gradation* is the distribution of different particles of aggregates by size. For example, grading is the relative amounts of particles ½-inch to ⅜-inch in size, ⅜-inch to ¼-inch in size, etc. in aggregates. Several gradation descriptions commonly used in the industry are as follows:

Well Graded: An aggregates product or blend in which the size of the aggregates particles are well distributed from coarse to fine. In other words, there are similar quantities of coarse, intermediate particles and fine sized particles.

Uniformly Graded: An aggregates product or blend in which most of the aggregates particles are nearly the same size.

Gap Graded: An aggregates product or blend in which most of the aggregates particles are either coarse or fine, with very few intermediate size particles present.

Aggregates gradation influences many mixture properties, including the mass stability and roughness or texture of the surface of the mixture. In general, the more well-graded the aggregates, the greater the strength of the mixture. The optimum grading for most construction applications is approximately the particle size distribution that allows the maximum amount of aggregates to be included in a unit volume of mixture. Exceptions to this include Macadam base which is composed of large, essentially one-size aggregates, typically 1-inch to 2-inch in maximum particle size and gap graded Stone Matrix Asphalt (SMA) mixtures. The aggregates grading also influences the workability of aggregates-binder mixtures. Mixtures made with well-graded aggregates are handled easily and their surface can be smoothly finished.

Unit Weight and Voids in Aggregates: The unit weight (density) of aggregates and the volume of voids in the aggregates mixture often need to be known for design of pavement mixtures. The test procedure commonly used to determine unit weight and voids is AASHTO Method T-19 (ASTM Method C 29). The aggregates are tested in either a loose or compacted condition. A container of known volume is used in the test. The size of container is increased as the nominal maximum size of aggregates to be tested increases. The sample is first dried and then placed in layers into the container by either jigging or shoveling in a prescribed manner, depending on maximum particle size. The dry unit weight is calculated by dividing the dry weight of material required to fill the container by the calibrated volume of the container. Voids between particles are calculated by the following formula:

$$\text{Voids (\%)} = \left| \frac{(A \bullet W) - B}{A \bullet W} \right| \bullet 100 \qquad (2\text{-}11)$$

where:

A = Bulk specific gravity, by AASHTO Method T-85
B = Unit weight of aggregates, by AASHTO Method T-19
W = Unit weight of water, 62.4 per cubic feet

Voids in aggregates mixture are the spaces between aggregates particles, i.e., the difference between the gross volume enclosing the aggregates and the volume occupied by just the aggregates particles (not including the space between particles).

The void space in an aggregates mixture is a function of aggregates grading, particle shape and texture and degree of compaction. For most construction applications, the voids in the aggregates mass should be minimized by using a dense-graded aggregates mixture. Maximizing mixture density is usually desired to provide the most durable construction or strongest mixture. This also minimizes binder requirements. Since the binder is more expensive than the aggregates, minimizing the binder required maximizes the economy of construction. Completely eliminating the voids in an aggregates mixture is generally not possible. Furthermore, some minimum volume of voids may be desirable depending on the application. In hot mix asphalt for example, a minimum volume of voids is usually required to allow the asphalt binder to occupy some space and allow a small volume of air voids in the mixture. Other exceptions include constructions having permeable base courses or open-graded surface friction courses.

Thermal Volume Change: *Thermal volume change* is the change in the volume of the aggregates produced by a variation in temperature.

Aggregates should have a coefficient of thermal expansion that is approximately the same in all directions and at all exposure temperatures. Further, all minerals present in the aggregates, ideally, should have the same coefficient of thermal expansion to prevent internal fracture of the aggregates. The coefficient of thermal expansion of aggregates ranges from 0.5 x 10-6 inches to 9 x 10-6 inches/inch/°F. When a significant difference exists between the coefficients of thermal expansion of the aggregates and a rigid binder, consideration should be given to use of a visco-elastic binder, such as asphalt, instead of a rigid binder, such as portland cement.

Thermal Conductivity: *Thermal conductivity* is the ability of an aggregates to transmit heat.

Aggregates and aggregates mixtures with low thermal conductivity are desired to decrease the depth of frost penetration through a pavement. Conversely, aggregates that transmits heat rapidly minimizes development of large differential temperatures between the top and bottom of a rigid pavement slab. A uniform temperature through the slab decreases the magnitude of stresses caused by bending of the slab due to a temperature gradient (often called curling) and also reduces cracking.

Integrity During Heating: *Integrity during heating* is the ability of an aggregates to retain desirable properties when subjected to high temperatures.

In the production of hot-mix asphalt concrete, the aggregates is dried by heating to temperatures of approximately 350° to 400° F. The aggregates must not be adversely affected by the high temperature so that the aggregates particles fracture, become weak or have other characteristics modified by heat.

Electrical Conductivity: *Electrical conductivity* is the ability of an aggregates to transmit electricity.

Construction aggregates should be able to conduct a certain amount of electricity in certain applications. A motor vehicle generates static electricity during its movement along the pavement. An electrical charge should not be allowed to build up and must be dissipated by traveling through the pavement to the ground. Also, the aggregates should not contribute to the development of static electricity when rubber tires rub on the pavement surface. If the aggregates conducts electricity, a build-up of static electricity is minimized.

If an aggregates product is used as a backfill material behind retaining walls or around other structures, a low level of conductivity is often desired. High levels of conductivity may indicate the presence of certain ions, such as chlorides, that could lead to corrosion in metal components of retaining walls or pipes.

Reflection: *Reflection* is the returning of light waves toward the source by the surface of an aggregates.

Although most aggregates have low reflectivity, reflective aggregates are often desirable to provide a contrast between a surface and its surroundings. Reflective aggregates increases the delineation of a road surface when the surface is illuminated by the lights of a motor vehicle. Also, use of reflective aggregates reduces the amount of power needed for night-time illumination of streets, intersections, and parking lots.

Glare: *Glare* is the reflection (shining) of a strong, steady and dazzling light from the surface of aggregates.

Light from oncoming cars and overhead lights creates a glare on the surface of some pavements. Bright, intense light decreases the night vision of the motor vehicle driver and creates a potentially hazardous condition. Aggregates used in the surface of a pavement should not create a glare condition.

Color: *Color* is the property of reflecting light waves of a particular wave length from aggregates particles.

Aggregates used for exposed construction should have a pleasing color. Vivid, contrasting colors are distracting and should be used only when a delineated surface is desired. Aggregates particles used in a particular mixture should be of uniform color.

Volume Change—Wetting and Drying: *Volume change due to wetting and drying* is a change in volume of the aggregates that occurs as the moisture content of the aggregates changes with time.

Aggregates should exhibit little or no volume change with variations in moisture content. Swelling or shrinkage volume changes produce disruptive forces that can cause cracking or pop-outs in the mixture. The magnitude of volume change due to wetting and drying generally is related to the volume of permeable pores in the aggregates.

Some forms of chert present in limestone aggregates exhibit undesirable volume change when exposed to moisture. The chert particles expand and can cause pop-outs when utilized in portland cement concrete.

Resistance to Wetting/Drying: *Resistance to wetting and drying* is the ability of an aggregates to resist cyclic wetting and drying (changes in moisture content) without cracking or breakdown).

Increases and decreases in the moisture content of aggregates produce internal stresses that cause cracking and slaking in some types of aggregates. Aggregates exhibiting this phenomenon should not be permitted in applications where water can gain access to it, such as in bound macadams and non stabilized bases and subbases. However, when the aggregates are used in combination with an impervious binder, such as asphalt, cyclic wetting and drying is not as important and less resistant aggregates normally can be used without encountering a durability problem.

Resistance to Freezing/Thawing: *Resistance to freezing and thawing* is the ability of aggregates to resist deterioration due to cyclic freezing and thawing.

Some types of aggregates deteriorate, i.e., undergo general flaking and cracking, when they are wet and then subjected to cycles of freezing and thawing. Deterioration occurs because water present in the pores of the aggregates expand during its transformation to ice, producing high internal stresses that fracture the aggregates. The resistance of the aggregates to freeze/thaw action is influenced by the volume and size of accessible pores in the aggregates. Aggregates used in areas where the number of freeze/thaw cycles is large should be resistant to this type of destructive force.

Deleterious Substances: *Deleterious substances* are those substances present in an aggregates that are harmful to the desired properties of aggregates-binder systems.

Harmful substances occasionally found in aggregates include: (1) structurally soft and/or weak particles, (2) clay and other types of surface coatings, (3) organic materials, (4) aggregates particles such as chert which exhibit disruptive expansion and (5) aggregates particles that react chemically. Soft aggregates, expansive aggregates and chemically reactive aggregates disintegrate rapidly when exposed to severe climatic situations that can result in failure of an aggregates-binder system. Coatings and organic material adversely affect adhesion between aggregates and binder and also result in a mixture that does not perform as intended. Deleterious substances should be minimized in aggregates used in construction.

Chemical Properties

Chemical properties identify a material chemically and/or indicate the transformation which a material undergoes due to a chemical process. Solubility, surface charge and resistance to chemical attack are examples of different chemical properties. Whenever aggregates undergoes a change due to a chemical action, the forces causing the change are usually from sources external to the system. However, in some instances, serious deterioration is produced by chemical action initiated by compounds that are components of the binder. To avoid this problem, the aggregates should be chemically compatible with the binder.

Solubility: *Solubility* is the tendency of aggregates to be dissolved by a liquid.

Since water is frequently present, aggregates should not be soluble in water. Frequently, the water is slightly acidic and readily dissolves carbonate rocks such as limestone. In some localities, water with unusual chemical contents is present, such as runoff from coal mine slag tailings which can be highly acid. The aggregates should not be soluble in these solutions either.

Slaking: *Slaking* is the crumbling of aggregates into visible particles when water or other liquids destroy the bond between its mineral grains and cause expansion of air inside the pores.

Hard clay lumps and shale are generally deleterious particles in aggregates partly because they slake when immersed in water for a short period of time. Aggregates should not slake in water or other liquids present in a pavement system.

Base Exchange: *Base exchange* is the replacement of one type of cat ion adsorbed on the aggregates surface by another type of cat ion.

Certain cat ions can be adsorbed onto the surface of aggregates particles. These cat ions promote the release of alkalies from adsorbed clay present in the aggregates. These alkalies can then react with portland cement concrete in the same manner as the reaction described in a later section on Chemical Compound Reactivity. Aggregates should have surface properties that prevent detrimental base exchanges.

Surface Charge: *Surface charge* is the distribution of electric charges on the surface of an aggregates.

Adhesion of an asphalt binder to an aggregates surface is influenced to a considerable extent by the polarity of the charge on the surface of the aggregates. Water can be strongly attracted to a highly polarized aggregates. This attraction can be so strong in asphalt concrete mixtures that the asphalt may not be able to displace the water and coat the aggregates. Proper surface electrical charges that produce good adhesion of asphalt to aggregates are needed on the surface of an aggregates.

Coatings: *Coatings* are a deposit of mineral and/or chemical substances on the surface of aggregates particles.

Some natural aggregates are coated with precipitated salts. Aggregates also may be coated with dust or clay. If coatings are firmly bound to the aggregates and are nonreactive with either the aggregates or the binder, the coatings may be quite acceptable. However, coatings should not be permitted if they prevent good adhesion between the aggregates and binder or if they react with the aggregates or binder.

Resistance to Attack by Chemicals: *Resistance to attack by chemicals* is the ability of an aggregates to resist deteriorating attacks from chemicals, such as deicing salts, which are carried into the pavement system in a solution with water.

Aggregates can react with salts, such as calcium or sodium chloride, that are placed on the pavement surface for winter maintenance. This reaction is accelerated by cyclic freezing and thawing. The resulting disruptive stresses can produce pavement deterioration. Aggregates should be resistant to deterioration caused by highly soluble chemicals and their presence should be anticipated.

Chemical Compound Reactivity: *Chemical compound reactivity* is the change in the structure of an aggregates produced by chemical reactions with the binder.

Chemical compounds, such as sulfates, may exist in the aggregates and react with certain binders used in mixtures. Compounds, such as alkalies, also can exist in the binder and may react with the aggregates. These chemicals can be quite detrimental to the integrity of the mixture. Regardless of the source of the detrimental compounds, the aggregates and binder should be chemically compatible.

Oxidation and Hydration Reactivity: *Oxidation and hydration reactivity* are chemical changes in an aggregates produced by exposure to atmospheric conditions.

Certain minerals may be present in aggregates that are affected chemically by *oxidation* (a reaction with oxygen) or *hydration* (a reaction with water) from atmospheric elements. The chemical oxidation process produces compounds such as iron oxide that discolor the surface of a pavement or concrete structure. Hydration reactions can produce particle expansion that results in pop-outs on the surface.

Oxidation and hydration reactions normally do not have a serious effect upon the strength or durability of the system in which the aggregates are used. Oxidation and hydration reactions do influence the aesthetics of the surface. Thus, minerals that produce surface stains or disfiguration should not be present in the aggregates used in a surface layer.

Organic Material Reactivity: *Organic material reactions* cause changes in the structure of mixtures due to a reaction of the binder with organic material in the aggregates.

Organic material exists in some types of aggregates. Organic material may react with ingredients of portland cement concrete, resulting in a decrease in strength and rapid deterioration of the concrete. Certain organic material should not be present in aggregates used in these mixtures. If aggregates for use in portland cement concrete mixtures contains reactive organic material that is harmful, the organic compounds should be rendered nonreactive during processing. Aggregates containing some organic material, such as asphalt, can be used successfully in asphalt concrete mixtures without modification.

Chloride Content: *Chloride content* indicates the concentration of chloride ions present in the aggregates particles.

Chlorides are among the more abundant chemicals on the earth and are present in variable amounts in all of the components used to make portland cement concrete. Aggregates having a high soluble chloride content can contribute to the corrosion of reinforcing steel used in concrete structures, metal pipes and the corrosion of tieback strips and anchors sometimes used in retaining wall construction. The threshold value for chloride content in concrete above which corrosion of the embedded steel occurs is as low as 0.15 percent by weight of cement. The presence of oxygen and moisture are also necessary for corrosion of the steel to occur.

Corrosion is an electrochemical process that results in an accumulation of corrosion products on the steel. Since the volume of the corrosion products is greater than that of the original components causing corrosion, stresses are developed in the concrete in the vicinity of the steel. Cracking occurs when the concrete cannot resist these stresses. The maximum permissible chloride content of the coarse aggregates used in reinforced concrete in a moist environment is approximately 150 ppm to 200 ppm.

Mechanical Properties

The mechanical properties of a material are the physical properties that identify the behavioral characteristics of the material when subjected to various types of applied forces. The more common mechanical properties include strength, stiffness (expressed, for example, as a resilient modulus), wear resistance and resistance to degradation.

Particle Strength: *Particle strength* is the magnitude of tensile and/or compressive stress that an individual aggregates particle can withstand before failure occurs.

In general, individual aggregates particles should have high strength. In hot mix asphalt and aggregates base, particle strength is extremely important since the aggregates particles carry most of the load. In concrete, loads are generally transmitted through the paste and since most aggregates particles have higher strength than paste mixtures, particle strength is of less importance.[3]

Determination of the strength of individual aggregates particles is difficult because the particles have varying shapes and sizes. Also, whether the strength of individual particles or the strength of the compacted aggregates mass should be evaluated is not always easy to determine.

Mass Stability: *Mass stability* is a property which permits a combination of aggregates particles to remain stable and retain their load-carrying capabilities under various types of loading.

Mass stability is a desired overall property of an aggregates combination or an aggregates-binder mixture. Mass stability is influenced by a number of properties related to the aggregates and the binder such as grading, shape, surface texture, etc. Loss of mass stability leads to surface rutting and/or cracking of the system in which the mixture is used.

Particle Stiffness: *Particle stiffness* is the resistance of an aggregates particle to deformation as usually indicated by the modulus of elasticity of the particle. The modulus of elasticity is equal to the applied compressive or tensile stress divided by the corresponding recoverable strain.

Many of the comments pertaining to particle strength are applicable to stiffness. Actual particle stiffness is rarely measured and is seldom used in design because of the problem of testing individual particles of varying size and shape. Tests to measure the modulus of elasticity normally are performed on rock core segments rather than actual aggregates particles. An aggregates with a high degree of stiffness is desired for most construction applications.

Wear Resistance: *Wear resistance* is the ability of an aggregates surface to resist being polished or worn away by rubbing and friction produced by externally applied forces, such as vehicle or foot traffic.

Aggregates used in a pavement surface layer must have resistance to polishing and wear by motor vehicle tires. The surface should wear non-uniformly to maintain a high level of surface friction. Since the rate of polishing is related primarily to the types of minerals in aggregates, a high percentage of hard, well-bonded mineral grains in a softer matrix should be present in the aggregates if it is to resist the abrasive smoothing action of tires.

Resistance to Degradation: *Resistance to degradation* is the ability of the aggregates to resist breakdown into smaller pieces when subjected to applied forces such as those produced by mixer blades, compaction, heavy wheel loads and autogenous grinding action.

Aggregates degradation is different from wear. When wear occurs the small pieces that abrade off the aggregates are brushed aside by moving tires and no longer influence the behavior of the system. However, when degradation takes place, the broken pieces of aggregates, which usually are larger than those abraded off during wearing, remain and contribute to the performance of the mixture. Degradation, as defined here, does not include breakdown due to chemical processes.

Resistance to degradation is especially important during aggregates stockpiling, handling, mixing and compaction. Aggregates that degrade easily may break down during these processes and change gradation. This gradation change can greatly affect how an aggregates mixture performs. In flexible pavement, as the system deflects and rebounds under dynamic loading, aggregates particles within the system also move. If this movement is relatively large and poor quality aggregates are used, the aggregates edges can be worn off, fracturing may take place and a general degradation of the aggregates can occur. If degradation occurs, consolidation of the unstabilized aggregates layer, and cracking and break-up of the upper layers of the system may result.

Degradation is especially important in poorly compacted, unbound aggregates base and subbase materials. Degradation also is important in aggregates located at the surface of a pavement. If aggregates particles on the surface degrade, loose particles may be thrown into the air by motor vehicle tires causing a potential hazard to a vehicle or its occupants. Degradation that occurs while an aggregates and binder are being mixed, or during compaction in the pavement, changes the original grading of the aggregates and causes changes in material properties that often are detrimental to the performance of the pavement.

Particle Shape of Abraded Fragments: *Particle shape of abraded fragments* is the spatial shape of the small fragments that are broken or worn away from an aggregates particle during abrasion.

Abrasion of the aggregates alone may not be detrimental. Whether or not abrasion is detrimental depends upon the characteristics of the particles abraded from the surface of the aggregates. If the abraded particles are rounded in shape and very small in size, polishing of the aggregates may result causing a reduction in surface friction. However, if rough aggregates is worn so that slivers are broken loose, new sharp fractures may develop resulting in surface roughness and high friction.

Resilient Modulus: *Resilient modulus* of a pavement material is a dynamic test response calculated by dividing the applied repeated axial deviator stress by the recoverable axial strain. The resilient modulus is a form of modulus of elasticity.

The resilient modulus is determined from a repeated load triaxial test where the confining pressure is held constant while a repeated dynamic load is applied to a cylindrical specimen of compacted material. Theoretical procedures for the design of pavement systems use the resilient moduli of each layer and the subgrade.

Certain fundamental design methods for asphalt concrete pavements, such as the Mechanistic-Empirical Pavement Design Guide (MEPDG) are based upon linear elastic layered models. These models assume the material in each layer to be linear elastic, isotropic and homogeneous. Two independent elastic material constants are required to characterize each layer and to compute the recoverable stress, strain and displacement response of the pavement system using elastic layered theory. The two elastic properties frequently used are the resilient (elastic) modulus and Poisson's ratio. Other elastic properties such as bulk and shear modulus also can be employed.

2.4 Physical Properties of Common Aggregates

The physical properties of several common types of aggregates particles are tabulated in Table 2.2. Information contained in this table includes the typical range of the specific property for each aggregates. Properties for which typical data are provided include: (1) unit weight, (2) compressive strength, (3) tensile strength, (4) shear strength, (5) flexural strength, (6) modulus of elasticity, (7) water absorption, (8) porosity, (9) thermal coefficient of expansion and (10) specific gravity.

Table 2.2 Typical Physical Properties of Common Aggregates[5, 6 7, 8]

Property	Granite	Limestone	Quartzite	Sandstone
1. Unit Weight (pcf)	162-172	117-175	165-170	119-168
2. Compressive Strength (x 10^3 psi)	5-67	2 6-28	16-45	5-20
3. Tensile Strength (psi)	427-711	427-853	NA*	142-427
4. Shear Strength (x 10^3 psi)	3 7-4 8	0.8-3 6	NA*	0.3-3 0
5. Modulus of Rupture (psi)	1380-5550	500-2000	NA*	700-2300
6. Modulus of Elasticity (x 10^6 psi)	4.5-8.7	4.3-8 7	NA*	2.3-10.8
7. Water Absorption (% by wt)	0.07-0 30	0.50-24.0	0.10-2 0	2 0-12.0
8. Avg. Porosity (%)	0.4-3 8	1.1-31.0	1.5-1.9	1 9-27 3
9. Linear Expansion (x 10^{-6} in./in./˚C)	1 8-11 9	0.9-12.2	7 0-13.1	4 3-13.9
10. Specific Gravity	2.60-2 76	1 88-2 81	2.65-2.73	2.44-2.61

NA = Data not available*

2.5 Measurement of Aggregates Properties

This section summarizes commonly used testing methods for characterizing selected aggregates properties. A list of AASHTO and ASTM specifications commonly used for aggregates together with a list of commonly used test procedures are given in the Appendix located at the end of this chapter.

Particle Size Analysis and Distribution

Dry Mechanical Sieving: Sieving consists of passing a known quantity of dry aggregates particles through a set of sieves. A round sieve having a diameter of 8 inches or 12 inches usually is used for fine aggregates. Coarse aggregates normally is sieved in a larger rectangular sieve about 15 inches x 23 inches size. The sieves have square openings formed by wire cloth with the wire thickness increasing as the size of the sieve openings increase. The standard opening sizes used in sieving are given in Table 2.3.

The sieves are stacked upon each other in order of decreasing sieve opening size from top to bottom. A pan is placed on the bottom to catch any particles passing the smallest size sieve. A mechanical sieve shaker usually is used, although shaking by hand is sometimes employed when the gradation of a small quantity of fine aggregates is to be determined. The stack of sieves is shaken by imparting either a vertical or vertical and horizontal motion which causes the particles to bounce up and down. The quantity of material used is limited by ASTM and AASHTO standard test procedures to prevent clogging of the sieves and thus permit the particles to move down to the sieve a number of times during shaking.

Table 2.3 Selected U.S. Standard Sieve Sizes (Adapted from ASTM E 11)

Sieve Designation		Nominal Sieve
Standard	Alternative	Opening, in.
75 mm	3 in	3
63 mm	2 ½	2.5
50 mm	2	2
37.5 mm	1 ½	1.5
25.0 mm	1	1
19.0 mm	¾	0.75
16.0 mm	⅝	0.625
12.5 mm	½	0.500
9.5 mm	⅜	0.375
6.3 mm	¼	0.250
4.75 mm	No. 4	0.187
3.35 mm	No. 6	0.132
2.36 mm	No. 8	0.0937
2.00 mm	No. 10	0.0787
1.70 mm	No. 12	0.0661
1.18 mm	No. 16	0.0469
850 µm	No. 20	0.0331
600 µm	No. 30	0.0234
425 µm	No. 40	0.0165
300 µm	No. 50	0.0117
250 µm	No. 60	0.0098
212 µm	No. 70	0.0083
150 µm	No. 100	0.0059
125 µm	No. 120	0.0049
106 µm	No. 140	0.0041
75 µm	No. 200	0.0029
53 µm	No. 270	0.0021
45 µm	No. 325	0.0017
38 µm	No. 400	0.0015

Test Method: Determination of the grading of a sample of aggregates by passing dried material through a series of standard sieves is described in AASHTO T-27 (ASTM C 136). The method covers both fine and coarse aggregates. To accurately determine the amount of material in a sample finer than the No. 200 sieve, this method cannot be used alone and wet sieving by Method AASHTO T-11 (ASTM C 117) should be used.

The method requires a minimum sample size be tested based on the aggregates nominal maximum size to ensure the sample tested is large enough to be representative of the entire aggregates product or stockpile. The dry sample is passed through a series of sieves using either hand or mechanical agitation. The result is tabulated as the percent of the original sample weight passing each sieve size tested. The results can also be plotted on a gradation chart showing sieve sizes along the x axis and percentages passing by weight on the y axis.

Standard 8 inch or 12 inch diameter sieves as defined in ASTM Specification E 11 may be used for particles finer than about the No. 4 sieve. If coarser particles are present, the sample may be split at the No. 4 size. The coarser fraction is sieved separately on larger screens using mechanical shaking and the finer fraction is shaken through standard 8-in. diameter sieves. When this procedure is followed, the percentage by weight of each size increment is computed based on the total sample weight.

Application: The method is widely used to determine if aggregates products or blends of aggregates meet required specifications.

Wet Mechanical Sieving: Dry sieving alone cannot accurately determine the amount of material passing the No. 200 sieve. Wet sieving is a standardized procedure used to separate the minus No. 200 size particles from the coarser particles using water. This is especially necessary when the coarser aggregates particles are heavily coated with fines.

In the wet test, the sample of aggregates first is dried to determine its initial mass then placed in water and agitated sufficiently to separate all the particles smaller than the No. 200 sieve from the coarser ones. The resulting wash water is passed through the No. 200 sieve to determine the percent by total weight of fines accurately. Fines are defined as clay and silt size particles smaller than the No. 200 sieve.

Testing is performed in accordance with AASHTO Method T-11 (ASTM C 117) which is a necessary supplement to Method T-27 (ASTM C 136). For fine-grained soils AASHTO Method T-88 (ASTM D 422) may be preferable since it permits use of a dispersing agent that ensures complete separation of clay particles in the finer fraction of the sample. The method enables determination of particle size distribution down to the 0.02 mm size, as suggested in ASTM Specification D 2940.

Alternate procedures are available for wet-sieving using either plain water or water to which a wetting agent has been added. Inter-laboratory studies using samples containing less than 1.5 percent passing the No. 200 sieve found no significant effect from the use of dispersing agents on the results. On soil-aggregates samples containing higher percentages passing the No. 200 sieve, a dispersing agent should be used to ensure satisfactory test results.

Coefficient of Uniformity: The slope of the grain size distribution curve, which is expressed as the *coefficient of uniformity* C_u is an important property that can be related to permeability and mass stability. The coefficient of uniformity (C_u) is defined as:

$$C_u = \frac{D_{60}}{D_{10}}$$

where:

C_u = Coefficient of uniformity
D_{60} = Sieve opening size (mm) through which 60% of the aggregates passes
D_{10} = Sieve opening size (mm) through which 10% of the aggregates passes

A value of C_u greater than six indicates a dense-graded (i.e., *well-graded*) material composed of a considerable range of particle sizes. A C_u value less than four indicates a uniformly graded (i.e., *open-graded*) material having a narrow range of particle sizes. Dense-graded aggregates is typically desirable for maximum stability, while more open gradings are chosen for high permeability. Section 12.3 of Chapter 12 discusses criteria for design of drainage and filter layers that use other critical sizes: D_5, D_{15} and D_{50}, determined from dry sieve tests on coarse drainage layer aggregates and wet sieving on the fine filter material.

Properties of Fines in Aggregates

Atterberg Limits: The *Atterberg Limits* are the liquid limit and plastic limit of the fraction finer than No. 40 sieve in aggregates, soil-aggregates and soil material. The Atterberg Limits are determined in accordance with AASHTO Test Methods T-89 and T-90 (ASTM D 4318).

Liquid Limit: Liquid limit (LL or W_L) is defined as the water content at which the minus No. 40 size fraction passes from a plastic to a liquid state. A sample of material is moistened thoroughly, stirred, kneaded and chopped with a spatula, then placed in the cup of the liquid limit device shown in Figures 2.1 and 2.2. After being leveled and trimmed to a depth of 10 mm, the moist soil is divided by a firm stroke of the standard grooving tool (Figures 2.1 and 2.2). Next the cup is lifted and dropped following a standard procedure until the groove flows shut for a distance of 13 mm. The soil is assumed to have reached its liquid limit when 25 blows to the cup cause the groove to close for the prescribed distance. Several trials usually are made and a flow curve is plotted to permit determination of the water content corresponding to the 25 blows.

Plastic Limit: The *plastic limit* (PL or W_P) is the lowest water content at which the minus No. 40 fraction remains cohesive enough to hold together when rolled with the fingers on a glass plate or sheet of unglazed paper into a thread ⅛ inch in diameter. The difference between the liquid and plastic limits is termed the *plasticity index* (PI or I_P).

When the sample lacks cohesiveness and cannot be rolled into a ⅛ inch diameter thread, it is reported as being non-plastic. The decision on when a sample can be rolled into a ⅛ inch thread or when the groove flows shut is subjective and depends on the experience of the tester.

Therefore, rejection of borderline material based on the results of Atterberg Limit tests is often the subject of controversy among the parties affected.

Sand Equivalent Test: The sand equivalent test, AASHTO T-176 and ASTM D 2419, is a rapid field-correlation test to indicate the relative proportion of sand size particles to plastic fines and/or dust in granular soil and fine aggregates that pass the No. 4 sieve. The term "sand equivalent" expresses the concept that most granular soil and fine aggregates are mixtures of desirable coarse particles, such as sand and fine particles, such as dust or clay. The sand equivalent test is not intended to replace other standard methods of particle size analysis of soils by sieving and sedimentation processes, such as AASHTO Method T-88 (ASTM D 422).

Test Method: In summary, a measured volume of soil or fine aggregates and a small quantity of flocculating solution (such as anhydrous calcium chloride, USP glycerin or formaldehyde in distilled water) are poured into a graduated cylinder of specified size. The contents are then agitated to loosen coatings from the sand particles. Next a tube is placed in the graduated cylinder and a flocculating solution is passed through the tube into the cylinder. This "irrigation" procedure flushes any coating from the sides of the cylinder and gives a good dispersion of the fine and coarse material. The specimen then is "irrigated" using additional flocculating solution to force the plastic fines into suspension. After a prescribed sedimentation period, the height of flocculated plastic fines suspended in the water and the height of sand in the cylinder are determined. The *sand equivalent* (SE) is defined as the ratio of the height of sand to the height of plastic fines reported as a percentage. Since several alternate procedures are available, the method used should be indicated in the report since different results may be obtained using different procedures.

Methylene Blue Value: The Methylene Blue Value Test, AASHTO T 330, is used to determine the quantity of potentially deleterious clays and other fine material in aggregates. In some cases, the material identified as plastic fines or clay in the sand equivalent test is not a clay material, but merely clay size particles. This is often the very fine aggregates dust produced from crushing. This fine material should not be considered as deleterious. The methylene blue value test can be used to determine if these fines are deleterious clay materials or innocuous dust of fracture.

Test Method: In summary, a 10 gram sample of material passing the No. 200 sieve is obtained from the aggregates to be tested. It is then mixed with water to form a slurry. Methylene Blue solution is added to the slurry in 0.5 mL increments and stirred for one minute. After the addition of each increment, a drop of the slurry is placed on a piece of filter paper. Methylene Blue additions are continued until a drop deposited on the filter paper forms a halo or ring around the drop. This is the point at which the aggregates sample cannot absorb any additional Methylene Blue. The Methylene Blue Value (MBV) is calculated as the ratio of the total milligrams of Methylene Blue added to the sample divided by the sample weight. According to the AASTHO standard, MBVs less than or equal to six are typically considered excellent, with values of seven to 12 considered marginally acceptable.

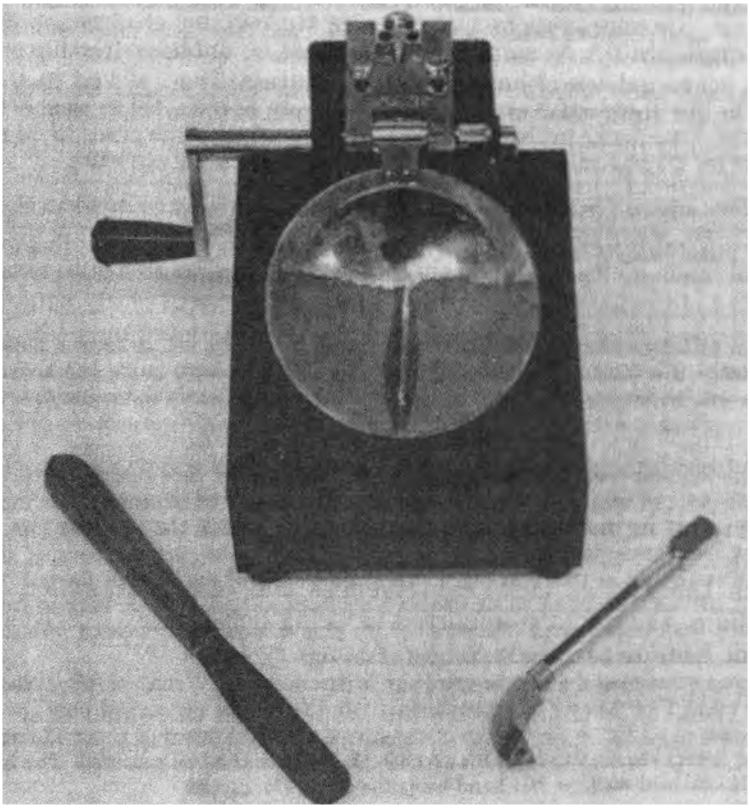

Figure 2.1 Grooved soil pat in liquid limit device, showing spatula and grooving tool.

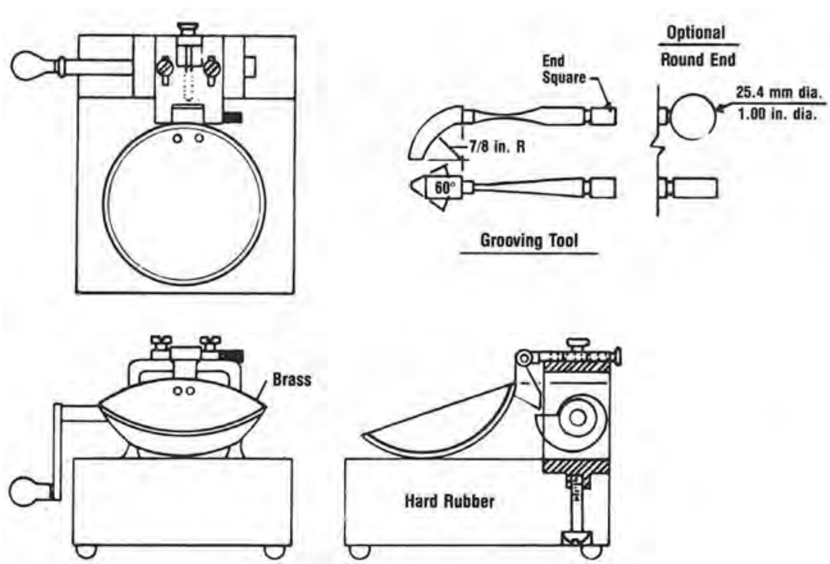

Figure 2.2 Detailed drawing of manual liquid limit device.

General Quality Tests

Certain inherent qualities generally are assumed to be related to the serviceability of aggregates produced from specific parent rock types. Among these qualities are hardness, toughness, soundness, volumetric stability, compressive strength, resistance to degradation and other forms of mechanical breakdown and resistance to polishing of pavement surfaces. In some cases these inherent properties may be altered through specialized processing techniques. The importance of any of these properties depends to a great extent upon the intended use of the aggregates; this fact must be borne in mind when evaluating aggregates and comparing one aggregates with another.

Many quality tests are at best approximate and consideration should be given to past performance of the aggregates. A number of areas related to aggregates are in need of research,[9] such as aggregates degradation and durability under varying service conditions.

Improved or new test methods are needed for evaluating aggregates that give good correlation with field performance.

Specific Gravity and Absorption of Fine and Coarse Aggregates: The specific gravity and absorption of fine and coarse aggregates are determined by AASHTO Test Methods T-84 and T-85 (ASTM C 128 and C 127), respectively. These tests are based on Archimedes' Principle, which he first proved in about 250 B.C. Archimedes' Principle states that a body of any kind, when immersed in water, is subjected to a vertical upward force equal to the weight of the water displaced by the body. As a result of this principle, an object submerged in water appears to weigh less than in air. Several definitions of specific gravity exist with the most commonly used definitions being:

Apparent Specific Gravity: The apparent specific gravity is the ratio of the weight of dry aggregates to the weight of water having a volume equal to the solid volume of the aggregates excluding its permeable pores.

Bulk Specific Gravity: This specific gravity is the ratio of the weight of dry aggregates to the weight of water having a volume equal to the volume of the aggregates including both its permeable and impermeable pores.

Bulk Specific Gravity—Saturated, Surface Dry (SSD): The SSD specific gravity is the ratio of the weight of the aggregates, including the weight of water it contains when its permeable voids are saturated, to the weight of an equal volume of water.

The specific gravity of a coarse aggregates is determined by the following three aggregates weights:

A = Weight of oven dry sample of aggregates in air.
B = Weight of saturated, surface dry sample in air. Usually the weight is measured after 24 hours of immersion in water followed by rolling the aggregates on a large, absorbent cloth until all visible films of surface water are removed.
C = Weight of saturated sample in water.

The apparent, bulk (dry) and saturated, surfaced dry specific gravities are then calculated using the three measured weights as follows:

$$\text{Apparent specific gravity} = \frac{A}{A-C} \tag{2-2}$$

$$\text{Bulk specific gravity, dry} = \frac{A}{B-C} \tag{2-3}$$

$$\text{Bulk specific gravity, SSD} = \frac{B}{B-C} \tag{2-4}$$

The water absorbed into the permeable voids, expressed as a percent, is calculated by the following formula:

$$\text{Water absorption (\%)} = \frac{B-A}{A} \cdot 100 \tag{2-2}$$

Fine Aggregates: To determine the SSD specific gravity of fine aggregates, a metal mold, in the form of a frustum of a cone, is filled with fine aggregates and tamped. The moisture content of the aggregates is reduced by drying and stirring until the aggregates slumps when the cone is removed. At this point the aggregates are taken as being in a saturated, surface dry condition. Usually, the volume of the sample is determined using a pycnometer, although measurement of sample weight in water could be used. This approach requires the use of equations that are different than those given above.

Determination of the saturated surface dry condition of fine aggregates using the conical metal mold can be troublesome. This is especially true for angular particles that do not slump readily. An alternate test method that has been developed is ASTM D 7172. In this test method, the saturated surface dry condition is determined automatically by a device that adds small increments of distilled water to the sample. As the water is added, the device uses an infrared light source and detector to observe the sample and determine the point at which water begins to collect on the aggregates surface. The metal cone method is still specified most often; however, the infrared technology as well as other techniques and procedures are being researched further.

Using the correct specific gravity is important in proportioning mixtures of aggregates and cementitious binders on the solid volume basis. The specific gravity value to be used in proportioning portland cement concrete must be consistent with the moisture condition assumed in the aggregates being batched-bulk dry specific gravity if aggregates weights are stated on a dry basis; bulk SSD if weights are on an SSD basis.[10] Bulk dry specific gravity is used to convert dry aggregates weights to the volume occupied in a mixture such as asphalt concrete. Apparent specific gravity is used to determine the solid unit weight of stone blocks but is seldom used in mix proportioning procedures.

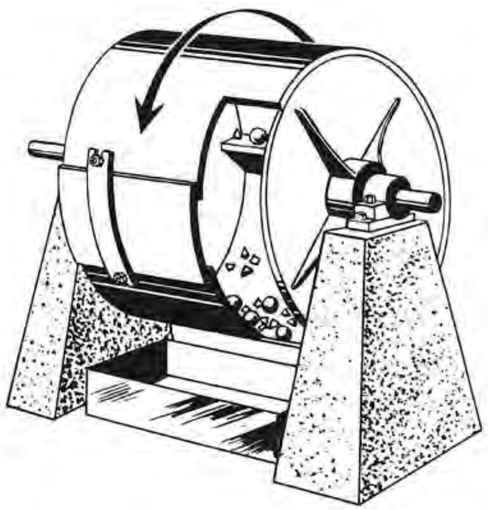

Figure 2.3 Los Angeles Degradation test machine.[11]

Los Angeles Degradation Test: The Los Angeles Degradation Test, AASHTO T-96 (ASTM C 131), is the most widely specified test for evaluation of the resistance of a coarse aggregates to degradation by abrasion and impact. The Los Angeles Degradation Test often is described erroneously as a hardness test. The test originally was developed in the Municipal Testing Laboratory of the city of Los Angeles in the mid-1920s. A 5,000-gm sample of aggregates having a specified grading is placed in a steel drum along with six to 12 steel balls each weighing about 420 gm. The drum used in the test is shown in Figure 2.3. The drum is rotated for 500 revolutions and a steel shelf within the drum lifts and drops the aggregates sample and steel balls about 27 inch during each revolution. The resulting vigorous tumbling action combines impact, which causes the more brittle particles to shatter, with surface wear and abrasion as the particles rub against one another and against the steel balls.

To perform the test, the aggregates sample first is washed and oven dried, and then separated into individual size fractions by sieving. Then the sieved material is recombined to the grading shown in Table 2.4 which most nearly corresponds to the size range to be used. Table 2.4 also indicates the number of steel spheres and the weight of each size fraction comprising the four standard gradations that can be used in the test. Following the completion of 500 revolutions, the sample is removed from the testing machine and sieved dry over a No. 12 sieve. The percent passing this sieve, sometimes termed the percent wear or percent loss, is the Los Angeles degradation value for the sample.

Table 2.4 Sample Size and Gradings for Los Angeles Degradation Test

ASTM C131 Gradings of Test Samples					
Sieve Size (Square Openings)		Mass of Indicated Sizes, g			
Passing	Retained on	Grading			
		A	B	C	D
37.5 mm (1 ½ in.)	25.0 mm (1 in.)	1 250 ± 25	—	—	—
25.0 mm (1 in.)	19.0 mm (¾ in.)	1 250 ± 25	—	—	—
19.0 mm (¾ in.)	12.5 mm (½ in.)	1 250 ± 10	2 500 ± 10	—	—
12.5 mm (½ in.)	9.5 mm (⅜ in.)	1 250 ± 10	2 500 ± 10	—	—
9.5 mm (⅜ in.)	6.3 mm (¼ in.)	—	—	2 500 ± 10	—
6.3 mm (¼ in.)	4.75 mm (No. 4)	—	—	2 500 ± 10	—
4.75 mm (No. 4)	2.36 mm (No. 8)	—	—	—	5 000 ± 10
Total		5 000 ± 10	5 000 ± 10	5 000 ± 10	5 000 ± 10

ASTM C535 Gradings of Test Samples				
Sieve Size, mm (in.) (Square Openings)		Mass of Indicated Sizes, g		
Passing	Retained on	Grading		
		1	2	3
75 (3)	63 (2 ½)	2 500 ± 50	—	—
63 (2 ½)	50 (2)	2 500 ± 50	—	—
50 (2)	37.5 (1 ½)	5 000 ± 50	5 000 ± 50	—
37.5 (1 ½)	25.0 (1)	—	5 000 ± 25	5 000 ± 25
25.0 (1)	19.0 (¾)	—	—	5 000 ± 25
Total		10 000 ± 100	10 000 ± 75	10 000 ± 50

Los Angeles Degradation Test for Large Size Aggregates: The Los Angeles Degradation Test procedure for testing coarse aggregates having larger sizes than permitted by AASHTO T-96 (ASTM C 131) is contained in ASTM Test Method C 535. The differences between these two test methods, which both are summarized in Table 2.4, include the sample sizes used (10,000 gm rather than 5,000 gm), the number of steel spheres used, the number of revolutions and test sample gradings. *Both ASTM methods C 131 and C 535 caution that the test results should be used only to indicate the relative quality of aggregates from sources having similar mineral composition. Also, test results do not automatically permit valid comparisons between sources distinctly different in origin, composition or structure.*

Sulfate Soundness Test: The Sulfate Soundness Test, AASHTO Method T 104 (ASTM C 88), is widely used as an index of general aggregates quality. The Sulfate Soundness Test is intended to provide an estimate of the resistance of aggregates to the weathering action that occurs in concrete and various other applications. The results of the Sulfate Soundness Test should be used with caution as indicated in ASTM Standard C 88: *"Since the precision of this test method is poor, it may not be suitable for outright rejection of aggregates without confirmation from other tests more closely related to the specific service intended."*

Test Method: In the Sulfate Soundness Test, the test sample is washed, dried and separated in specified size fractions. Each sample then is immersed into a saturated solution of sodium or magnesium sulfate for a period between 16 and 18 hours at a temperature of 70 ± 2°F. Next, the sample is removed and permitted to drain for 15 ± 5 min. and placed in a drying oven kept at a temperature of 230±9°F until constant weight is achieved. Usually the sample is subjected to five cycles of immersion and drying. During the immersion cycle, the sulfate salt solution penetrates the permeable pore spaces of the aggregates. Complete oven drying dehydrates the sulfate salt precipitated in the pores. The internal expansive force, derived from the re-hydration of the sulfate salt upon re-immersion, is intended to simulate the expansion of water upon freezing.

After completion of the required number of immersion and drying cycles, the sulfate salt is washed out of the sample and dried. The sample then is sieved through specified sieves somewhat smaller than the original sieves on which a given size fraction was retained. The resulting weighted average loss for each size fraction is used as the indication of durability of the aggregates. Following AASHTO specification M 283, typical limits for the sulfate soundness loss for various classes of aggregates are given in Table 17.2 of Chapter 17.

Freeze/Thaw Tests: The test method for resistance of concrete to rapid freezing and thawing (AASHTO T-161 and ASTM C 666) is often used as an indicator of aggregates soundness and general quality. This freeze/thaw test measures the resistance of concrete containing an aggregates being evaluated to rapid freezing and thawing. In one procedure, both freezing and thawing are performed in water; in another, freezing is performed in air and thawing in water. The test method that most closely simulates environmental conditions existing in the field should be selected unless the method is defined by project specifications.

Equipment: The freeze/thaw test requires a suitable chamber in which the specimens are subjected to the specified freezing and thawing cycles. The chamber must have the necessary refrigerating and heating equipment and controls to produce continuous freeze/thaw cycles automatically within the specified temperature requirements. A dynamic testing apparatus also is required to measure the fundamental transverse, longitudinal and torsional frequencies of the concrete specimens tested. For the purpose of calculating the dynamic modulus of elasticity, the specimens must be prisms from 3 inches to 5 inches in width, depth, or diameter and 11 inches to 16 inches in length. Specimens are molded either in the laboratory or sawed from hardened concrete in a pavement or other type of structure.

Test Results: Cured concrete specimens usually are subjected to 300 cycles of freezing and thawing, until the dynamic modulus of elasticity of each specimen drops to 60 percent of its original value or until the specimens fail completely, whichever occurs first.

The relative dynamic modulus is used to calculate a durability factor as follows:

$$DF = P \bullet N/M \quad (2\text{-}6)$$

where:

DF = Durability factor of the test specimen
P = Relative dynamic modulus of elasticity at N freeze-thaw cycles (%)
N = The smaller of either (1) the number of cycles at which P reaches the specified minimum value for discontinuing the test, or (2) the specified number of cycles for terminating the test
M = Specified number of cycles for terminating the test

A typical acceptable level for DF is 70 percent. Some agencies base aggregates acceptance only on the durability factor (DF), while others base acceptance on both DF and expansion of the specimen which is measured in the test. The length change is believed by some engineers to be more closely related to D-cracking of concrete pavement than changes in dynamic modulus. One state requires a minimum durability factor of 95 percent and a maximum expansion of 0.025 percent after 300 cycles as criteria for acceptance of concrete for interstate highway pavement.[12] Both the aggregates and the portland cement paste affect the test results.

Alternate for Sulfate Soundness Test: Freeze/thaw tests can be used as an alternative for the Sulfate Soundness Test. In particular, AASHTO T 103 is designed to furnish information helpful in judging the soundness of aggregates subjected to weathering. This test can be used when adequate information is not available from service records of the behavior of a particular aggregates. Freeze/thaw tests are of questionable value in predicting resistance to weathering in service. Past performance of an aggregates is a better indicator. Furthermore, aggregates freeze/thaw testing can be a lengthy process taking a matter of weeks or months to complete based on the number of freeze/thaw cycles required.

Micro-Deval Test: The Micro-Deval test is an abrasion test that has been shown to correlate well with aggregates performance in hot mix asphalt, portland cement concrete and base courses. Developed in France in the 1960s, it became popular in the United States in the late 1990s. A study by the International Center for Aggregates Research (ICAR Report 507-1F) indicated that the Micro-Deval test was the best single indicator of performance for hot mix asphalt, portland cement concrete, aggregates base course and open graded friction course when compared to other tests such as Los Angeles Degradation, sulfate soundness and specific gravity.[13]

The test is performed in accordance with ASTM D 6928 (AASHTO T 327) for coarse aggregates and ASTM D7428 for fine aggregates. A sample of aggregates are prepared to a standard grading. The sample is first soaked in water. The sample and water are then placed in a cylindrical container along with 9.5mm diameter steel balls. The container is then revolved at 100 rpm for a specified period of time depending on the grading of the sample. Upon completion of the test, the sample is screened over a specified sieve. The percent loss is considered the abrasion value. The Micro-Deval test is not currently used by many specifying agencies such as state departments of transportation; however its good correlation to field performance indicates that it may be specified more in the future. The Micro-Deval also has proven to be a very repeatable test unlike other tests, such as sulfate soundness.

Quality Tests—Particle Shape and Texture

Flat, Elongated or Flat and Elongated Particles: Particle flatness and elongation is determined by ASTM Test Method D 4791. This method provides three definitions for particle shape as follows:

1. Flat: Particles having a width to thickness ratio greater than a certain value
2. Elongated: Particles having a length to width ratio greater than a certain value
3. Flat and Elongated: Particles having a length to thickness ratio greater than a certain value

The definition of flatness and elongation that is used varies with the application. In most hot mix asphalt applications, only the third definition for flat and elongated particles is used. Other applications, such as railroad ballast, may refer to the total percentage of flat particles and elongated particles as shown in the first and second definitions. Individuals responsible for writing specifications should make it clear which definition should be used.

The test measures individual coarse particles using the proportional caliper shown in Figure 2.4. The proportional caliper is set to the ratio as defined by the specifications, typically 5:1 or 3:1. Depending on what is being measured, flatness, elongation, or flat and elongated, the maximum dimension can be quickly compared to the minimum dimension. Particles that are deemed to be flat, elongated or flat and elongated are separated and either weighed or counted. The percentage of particles determined to be flat, elongated or flat and elongated is expressed as a percentage of total mass or total particle count.

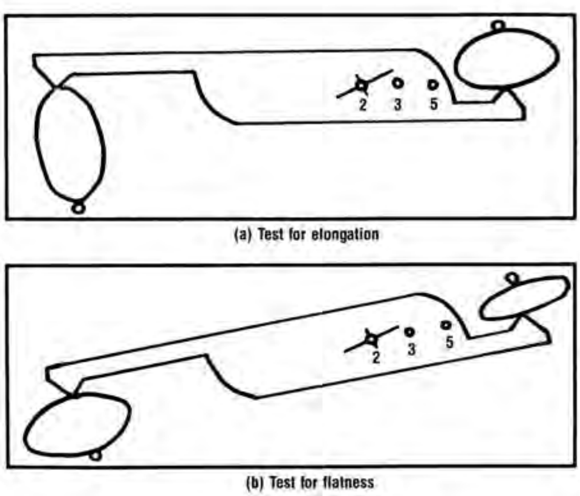

Figure 2.4 Flatness-elongation test caliper

Note: The caliper shown in this figure currently is set for a 2:1 ratio.

Fracture Particles in Coarse Aggregates: Many specifications require aggregates particles to have a minimum number of crushed surfaces or fractured faces. Generally, a high fractured face content is associated with a higher level of angularity. The test methods for determining the percentage of fractured faces in an aggregates product are ASTM D 5821 and AASHTO TP 61. In each of these procedures, coarse aggregates particles representing each size fraction in the product are individually inspected to determine the number of fractured faces present on that particle. The particles are then grouped according to the number of fractured faces. The fractured face percentage is then determined based on mass or count. Typical specifications require a minimum of percentage of particles with one fractured face and/or a minimum with two fractured faces.

Fine Aggregates Angularity: The angularity of fine aggregates are more difficult to determine visually due to the size of the particles. Fine aggregates angularity is therefore determined indirectly as a function of the uncompacted void content in accordance with ASTM D 1252 (AASHTO T 304). In this method, a sample of fine aggregates are allowed to free flow into a container of known volume. The weight of the material required to fill the container, the volume of the container and the specific gravity of the material are then used to calculate the volume of voids between the particles. Theoretically, angular aggregates particles will result in a higher void content due to the irregular shape of the individual particles. Rounded particles will tend to arrange themselves more closely resulting in lower void contents.

One potential problem with this test is that very cubicle particles, although they are angular, may act as rounded particles therefore resulting in lower void contents. Furthermore, flat and/or elongated particles may perform well in this test due to their particle shape. It has been established however that flat and/or elongated particles are generally not desirable. Because of these potential deficiencies, research is ongoing to identify a procedure to more accurately quantify fine aggregates angularity.

Particle Shape and Texture Test: Particle shape and texture also can be indicated in terms of percent voids measured on samples prepared at specified gradations and degrees of compaction.[15] In the Index of Aggregates Particle Shape and Texture Test (ASTM Method D 3398), each size fraction is compacted with a standard tamping rod into a mold 6 inches in diameter and 7 inches high, using two levels of compaction effort. The particle index is computed from the following formula:

$$I_a = 1.25\ V_{10} - 0.25\ V_{50} - 32.0 \qquad (2\text{-}7)$$

where:

I_a = Particle Index for a given size fraction

V_{10} = Voids in the aggregates when compacted using 10 standardized blows per layer

V_{50} = Voids in the aggregates when compacted using 50 standardized blows per layer

A weighted Particle Index is calculated by using the data for each size group present in a representative sample.

Quality Tests—Evaluation of Frost Action

Heave tests can be performed to evaluate the tendency of fines (silt and clay) present in aggregates material to change volume (heave) as a result of frost action in the presence of moisture. Both the U. S. Army Cold Regions Research and Engineering Laboratory (CRREL) and the British Transport and Road Research Laboratory (TRRL) have developed tests designed to subject compacted specimens to *directional freezing* (i.e., freezing from the top down) after exposure to capillary saturation.[16]

TRRL Test Procedure: The test equipment used for the TRRL procedure is shown in Figure 2.5. Following the TRRL procedure, cylindrical specimens 4 inches in diameter by 6 inches high are placed in a special self-refrigerated unit where the air temperature above the specimen is maintained at -17° ± 1°C. Each specimen rests on a porous ceramic disc in contact with water maintained at constant level and at a temperature of +4° ± 0.5° C. A push rod bearing on a cap resting on top of each specimen enables the heave to be measured. The total heave after 96 hours, or the rate of heave per day, is compared to suggested criteria to estimate susceptibility to frost. For example, an average four-day heave of 10 mm to 12 mm is considered excessive. Efforts have continued for some years to establish correlations between heave test results and actual field performance, with only limited success being achieved.

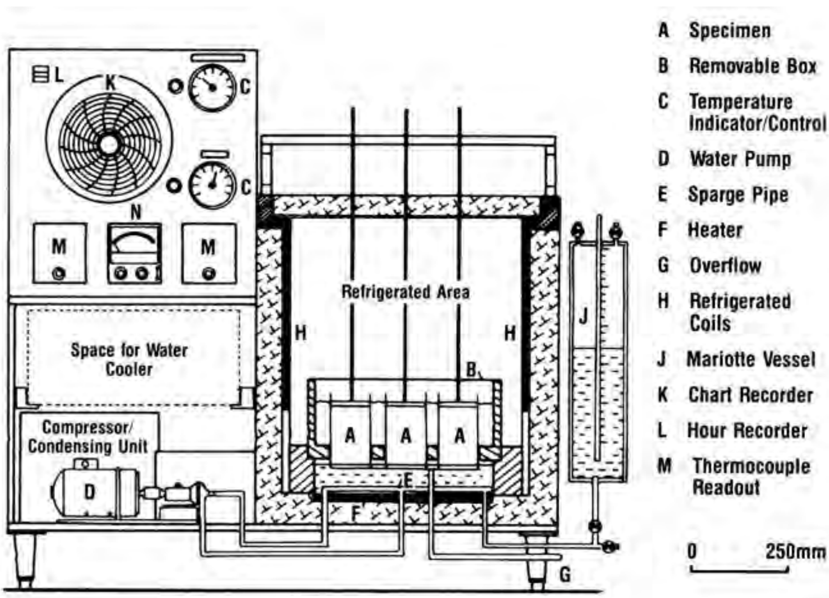

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Figure 2.5 Refrigerated unit for frost heave test.[16]

Heave Correlations: Laboratory heave tests to define frost action potential are not routinely performed. Instead, correlations such as those given in Figure 11.36 of Chapter 11 usually are used relating soil type to anticipated heave. These correlations are based on the soil classification and percent of material finer than 0.02 mm in size.

Additional Quality Tests

A number of test methods used to evaluate aggregates quality currently are not included in ASTM or AASHTO standards. The Page Impact Test and several other tests, including the Scratch Hardness, Dorry Hardness and Deval Abrasion tests, that once were considered standard, are now not commonly used.[17] Some of these tests have been shown to either be lacking in precision or not closely related to in-service performance and hence have a limited value for use in specifications. Selected non-routine test methods are described in this section, including several popular British tests.

The Mill Abrasion Test: The Mill Abrasion Test is used for the evaluation of ballast quality.[18] A test sample is prepared by combining 3.3 pounds of 1½ inch to 1 inch aggregates with 3.3 pounds of 1 inch to ¾ inch aggregates. The combined aggregates sample is washed and then oven dried in accordance with the Los Angeles degradation procedure. The dried aggregates then are placed in a one gallon, porcelain ball mill pot and 6.6 pounds of distilled water is added. The mill pot, which has a 9 inch external diameter, is sealed and rotated at 33 rpm for a total of 10,000 revolutions (five hours). The sample then is washed through a No. 200 sieve, oven dried and weighed. The percentage loss through the No. 200 sieve is the mill abrasion value, calculated by the following equation:

$$\text{Mill abrasion} = (\text{loss in weight}/\text{original weight}) \times 100 \qquad (2\text{-}8)$$

Abrasion Number: A parameter termed Abrasion Number (AN) has been found to be related to railroad ballast life. The Abrasion Number is obtained by combining the results obtained from the Mill Abrasion and Los Angeles Degradation tests:

$$\text{Abrasion Number} = \text{Los Angeles Loss} + (5 \times \text{Mill Abrasion Value}) \qquad (2\text{-}9)$$

Page Impact Test: The toughness of rock is defined as the resistance to fracture from impact and it closely is related to the absence of brittleness. The *Page Impact Test* was at one time standardized as ASTM Method D 3 and AASHTO Method T-5, however both methods have since been withdrawn. The Page Impact Test measures the resistance to impact of a 1 inch diameter cylindrical core specimen that is 1 inch high when resting on a solid foundation. Impact is applied by a 2-kg, (4.4-lb) hammer dropped freely between guides onto a spherically headed plunger resting on top of the specimen. The first blow is applied from a height of 1-cm (0.4-in.), the next from 2-cm (0.8-in.), the next from 3-cm (1.2-in.), etc. The height of drop in centimeters causing fracture of the specimen is reported as the toughness value.[17]

Aggregates Impact Value (AIV): The Aggregates Impact Value testing apparatus is illustrated in Figure 2.6. A standard sample of ½ inch to ⅜ inch aggregates particles is placed in a cylindrical-shaped, rigid mold and subjected to 15 blows from a 30-pound drop hammer falling through a height of approximately15 ± ¼ inches Degradation created in terms of percent passing a British Standard 2.40 mm sieve, which corresponds to approximately the U.S. Standard No. 8 sieve size, is designated the Aggregates Impact Value (AIV)[16]. Reproducibility of test results is high and the apparatus is relatively portable. This test measures particle toughness similarly to the way the Page Impact Test measures toughness of a single core specimen.

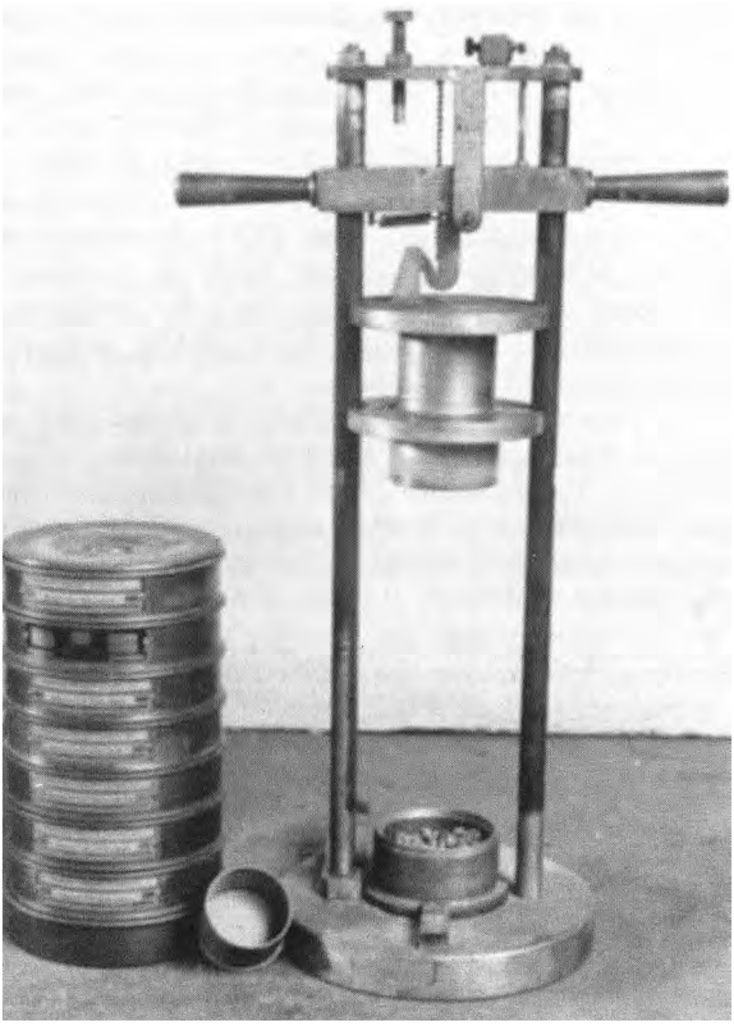

Figure 2.6 Aggregates impact value (AIV) apparatus.

Aggregates Crushing Value (ACV): In the Aggregates Crushing Value Test,[16] approximately 4.4 pounds of aggregates having the same size range as used in the Aggregates Impact Value Test is placed in a rigid cylindrical mold and subjected to a continuous load transmitted through a piston in a compression test machine illustrated in Figure 2.7. A load of approximately 90,000 pounds is applied gradually over a period of 10 minutes. The Aggregates Crushing Value is equal to the percentage of fines created that pass the British Standard (BS) 2.40 mm sieve expressed as a percentage of the initial sample weight.

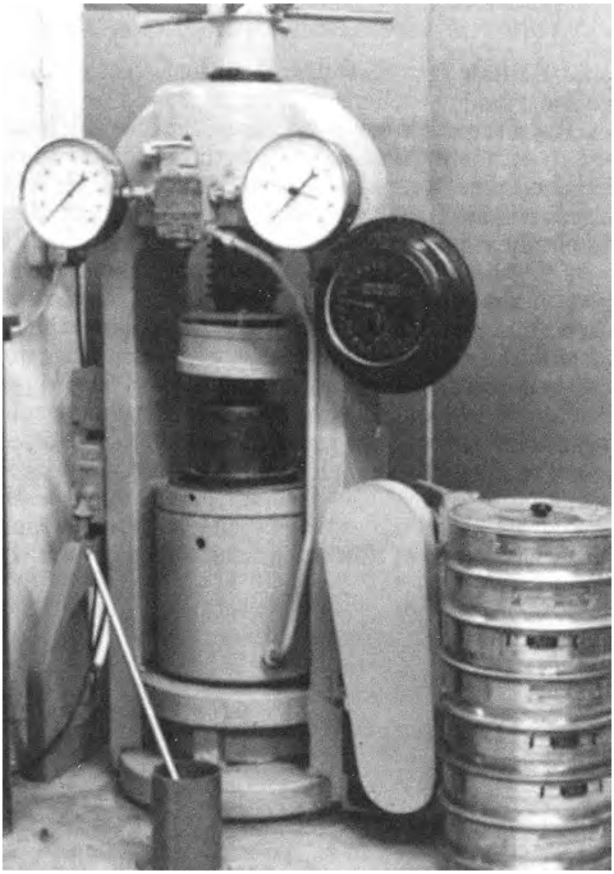

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Figure 2.7 Aggregates crushing value (ACV) apparatus.

The Aggregates Crushing Value and Aggregates Impact Value test results are indices of resistance to pulverization due to an externally applied load over a prescribed interval or sequence of loading. Variations in results of these tests within specific rock categories or between broader rock groups are attributed to the influence of aggregates particle shape and geological features such as structure and mineral composition. Use in these tests of the arbitrary cutoff level of BS 2.40 mm sieve size (approximately the U.S. No. 8 sieve) as the sole index of particle pulverization is somewhat misleading without considering other characteristics such as particle shape.[16] Modifications of these test methods have been investigated to produce a better characterization of the pulverization products. The Aggregates Crushing Value and Aggregates Impact Value tests are used in the United Kingdom as alternatives to the Los Angeles Degradation Test.

Schmidt Rebound Number: The Schmidt concrete test hammer, widely used to estimate the in-situ strength of concrete in the United States, also is used as a non-destructive test for rock (refer to Figure 2.8). The test method for this procedure is ASTM D 5873. An experienced geologist or engineer can use the Schmidt hammer to obtain a qualitative indication of the toughness, elasticity and state of freshness of a rock. The instrument is held tightly against the rock or concrete to be tested. A spring-loaded hammer or piston, when released, travels through a fixed distance, applying a known energy input to the rock. Because of the elasticity of the rock, the hammer rebounds away from the surface.

The amount of rebound is shown on a scale that is part of the apparatus and is termed the rebound number. Fresh igneous rock gives rebound numbers of 50 or higher. Where weathering is present or the rock is more porous, the Schmidt hammer is sensitive to the changes and gives lower values. Portability and ease of operation in the field is an advantage of this equipment.

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Figure 2.8 Schmidt hammer for rebound test.

Quality Tests Currently Under Development

The aggregates industry continues to develop new tests and equipment to improve aggregates characterization. One example of developing technology is imaging technology for aggregates.

Imaging Technology: Digital imaging is a technology that has shown great promise for use in determining aggregates gradations and particle shape. In summary, this technology uses a camera to obtain a digital image of a sample of aggregates particles. These images are then analyzed by specialized software that converts the images to basic geometric shapes and then measures the dimensions of these shapes. The resulting data then can be used to determine the gradation of the sample and in some cases, the quantity of flat and elongated particles. Once this technology is fully developed, it may be possible to use it both in the laboratory and in aggregates processing plants to determine aggregates gradations in near real-time. A summary of these technologies is available in the International Center for Aggregates Research reports 503-1, 503-2 and 503-3F.[20, 21, 22]

A similar device, the Aggregates Imaging System (AIMS), has been used extensively by ICAR researchers for the determination of aggregates shape and surface texture characteristics. This technology uses a camera as well as a video microscope to capture images of aggregates samples. The AIMS software then processes these images using a variety of techniques to determine three dimensional form, angularity and surface texture. Characterization results from the AIMS have correlated well with laboratory performance tests and show the promise of becoming a valuable tool in the future.[23]

Aggregates Base Moisture/Density and Permeability Tests

Moisture/Density: Moisture/Density Tests for Soils and Soil-Aggregates Mixtures, AASHTO Methods T-99 and T-180 (ASTM D 698 and D 1557), are widely used in compaction control of aggregates base. These tests were developed originally to establish optimum moisture content and acceptable density values for embankment soils. The procedures involve compacting a sample in a standard size mold by either dropping a 5.5-pound rammer from a height of 12 inches (Test Method AASHTO T-99) or a 10-pound rammer from a height of 18 inches (Test Method AASHTO T-180). The AASHTO T-99 method is commonly referred to as the "Standard Proctor" and the T-180 method as the "Modified Proctor" test. The size of mold used is either a 6-inch diameter or 4-inch diameter depending on the grading or maximum size of the sample.

Test Description: The material to be tested is dried either in air or in an oven such that the temperature does not exceed 140° F. Oversize particles as defined by the method are removed and discarded (i.e., scalped). The remaining material is mixed thoroughly with sufficient water to dampen it to approximately 4 percent below the estimated optimum moisture. The material then is tamped into the mold in layers (three layers in the T-99 procedure, five layers in T-180). After compaction, excess material is struck off even with the top of the mold. Tamping of each layer consists of 25 blows when a 4 inch mold is used, or 56 blows for a 6 inch mold. This procedure produces a compaction energy per unit volume that is approximately equal for each mold size and either AASHTO T-99 or T-180 compaction energies.

The compaction procedure is repeated using new material with water added in increments, so as to increase the moisture content by 1 percent or 2 percent. Water is added and additional specimens are prepared until there is either a decrease or no increase in the calculated dry weight/cubic feet of the compacted sample. Usually five specimens are required.

Test Results: A portion of material is removed from each compacted specimen and dried to determine its actual moisture content. The *moisture content*, expressed as a percent, is equal to the weight of water divided by the weight of dry solids multiplied by 100. The *wet density* of each compacted specimen is equal to the wet weight of each specimen divided by its volume. The *dry density* is calculated as follows:

$$\gamma_d = \frac{\gamma_w}{1 + w} \quad (2\text{-}10)$$

where:

γ_d = Dry density (pcf)
γ_w = Wet density (pcf)
w = Water content expressed as a *decimal*

The dry density usually is expressed in units of pounds per cubic foot (pcf). The term dry unit weight is often interchanged for dry density.

The maximum dry density, for a *particular test series*, is determined by plotting the dry density of each specimen on the y axis and the corresponding moisture content on the x axis. A moisture-density relationship is illustrated in Figure 17.2 in Chapter 17. The maximum dry density corresponds to the peak dry density on the compaction curve. The optimum moisture content is the moisture content that gives the maximum dry density.

Implications: The optimum moisture content and maximum density are not fundamental properties of a material. Different maximum dry densities and optimum moisture contents are obtained depending on whether AASHTO T-99 or AASHTO T-180 is used. *Therefore, the density test procedure used always must be given when a maximum dry density is discussed or specified.* Further, many aggregates gradings do not produce a well-defined peak on the moisture-density curve due partly to the inability of the particular grading to hold water during the test. When the water drains rapidly to the bottom of the mold, invalid test results are obtained.

Moisture-density control, including how to adjust the result to account for oversize particles in the aggregates, is discussed in Chapter 17. Another laboratory test method (ASTM Method D 4253), more applicable to free draining soil and soil aggregates, uses a vibratory table and also is discussed in Chapter 17. The objective of laboratory density testing is to define a dry unit weight to be used as a target density to which the material must be compacted in the field. Required density levels are always included in project specifications.

In-Place Density: Tests for determining the density of soils in-place by volume-of-hole methods (AASHTO T-191 or ASTM D 1556 and D 2167) are discussed in Chapter 17. These tests involve removing about 1⁄10 cubic feet of compacted material from the layer, determining its dry weight and measuring the volume of the hole from which the material was taken. The volume of the hole is determined by filling the hole with a substance, such as sand, water or heavy oil, whose unit weight has been pre-determined. The most accurate density test method for a rough-sided hole in an aggregates base layer involves determining the volume of the hole using water contained in a thin rubber membrane (ASTM D 2167).[24]

The volume of the excavated hole should be at least 86 cubic inches when the maximum aggregates size is ½ inch and 173 cubic inches for 2 inch maximum size aggregates.

Nuclear Moisture-Density Methods: The nuclear moisture-density tests (ASTM D6938 or AASHTO T 310) currently are the most widely used methods for measuring in-place density of aggregates base on highway and airport projects. The total wet density of the material is found by placing a gamma ray source and detector either into or on top of the layer to be tested. The intensity of the radiation detected is dependent in part upon the wet density of the material being tested. The moisture content is determined using a fast neutron source and a thermal neutron detector placed directly on the material being tested. Most modern nuclear equipment measures both density and moisture at the same time and presents a digital readout of dry density for comparison with the target density specified.

An important advantage of using nuclear methods is that they are much more rapid than other conventional tests. Limitations of the nuclear moisture-density method are given in Section 17.5 of Chapter 17. Density is most accurately determined by the direct transmission method where the gamma ray source is inserted into a small hole in the layer being tested. The backscatter method is less accurate since the measured density (and moisture content) is primarily affected by the top 1 inch or 2 inches of the compacted layer.

Non Nuclear Gauges: The purpose of compacting soils and base materials is to improve their engineering properties, particularly stiffness. Because density is relatively easy to measure and strongly related to stiffness, it has become the standard for field control. Recently however, a handheld device has been developed by the Federal Highway Administration and others that directly measures the in-place stiffness of soils and base materials.[25] This device, called the soil stiffness gauge (SSG), works by applying a vibrating force onto the surface of the material and then measuring the resulting displacement. The standard test method for the SSG is ASTM D 6758, however it is not in widespread use at this time. In general, field control is still accomplished most often using nuclear density equipment.

Aggregates Base Permeability: Laboratory evaluation of the permeability of aggregates by the constant head method frequently is performed in accordance with AASHTO Method T-215 (ASTM Method D 2434). However, problems are associated with the determination of the permeability of open-graded aggregates because flow through these materials tends to become turbulent and nonlaminar. Frequently, the coefficient of permeability (k) is estimated from empirically derived relationships such as those given in Section 12.2 of Chapter 12.

The laboratory permeability test is performed by first compacting a sample of the material in a cylindrical, rigid wall laboratory permeameter. Ideally, the sample should be compacted to the density required of the material in the field. The device is constructed such that water can be introduced into the top of the permeameter and exit at the bottom. Outlets are provided at points along the length of the permeameter to measure the changes in head. The sample is first saturated to remove any entrapped air. Water is then allowed to flow into the top of the permeameter, through the sample and out the bottom. The coefficient of permeability is determined using the measured head loss, cross sectional area of the sample and flow rate of water through the sample.

Tests for Mass Stability

Resilient Modulus: The resilient modulus test measures the elastic response of pavement materials to load and is used in flexible pavement design. The standard test method for resilient modulus is AASHTO Method T 307.

The resilient modulus is a measure of stiffness and is equal to the applied dynamic axial stress divided by the induced resilient (recoverable) strain. The test is performed by compacting a sample of soil or base material into a cylindrical mold, preferably to the specified field density. The compacted sample is enclosed in a triaxial chamber and exposed to a series of confining pressures. At each confining pressure, a series of repeated dynamic axial loads are applied to the top of the specimen. Each load series consists of 100 applications of a 0.1 second load followed by a 0.9 second rest. The deformation of the sample with each load application is recorded. The resilient modulus is calculated for each loading series by dividing the average axial load by the average recoverable deformation.

> *Application:* The resilient modulus test is a relatively complicated procedure for estimating the dynamic elastic modulus of untreated soils and aggregates. The use of varying confining pressures and axial loads is intended to simulate stress states existing beneath flexible pavements subjected to moving wheel loads. The resilient moduli of the layers of a pavement, together with the pavement geometry and loading conditions, determine the tensile strain in the bottom of the asphalt concrete and the compressive strain (or stress) on top of the subgrade. Calculated tensile strain in the bottom of the asphalt concrete is used in estimating the fatigue life of a pavement. Fatigue life is expressed as the number of equivalent 18 kip single axle loads (18k ESALs) required to cause cracking of the pavement surface. Vertical compressive strain is used, as an approximation, to limit permanent deformation in the subgrade.

The resilient modulus of an aggregates base material having 1½ inch maximum size aggregates should be determined from specimens at least six inches in diameter. The large aggregates in the base should not be scalped out to permit testing of smaller specimens. Removal of the large aggregates may result in a lower modulus and greater permanent deformation than if a specimen large enough to accommodate the actual gradation were used. Use of still larger specimens, however, may introduce more variability into the results.

California Bearing Ratio: The California Bearing Ratio (CBR) Test, AASHTO T-193 (ASTM D 1883), is used to evaluate and classify the support value of laboratory-compacted soil, soil-aggregates combinations and aggregates base. The test indicates resistance of the material to a punching shear failure. In this test, a specimen is compacted at optimum moisture content. Aggregates particles larger than ¾ inch in size are not included in the test specimen. Therefore, the test gives conservative results, i.e., a low CBR value, for subbase and base materials containing top aggregates sizes greater than ¾ inch.

Test Description: A CBR test can be performed either on samples compacted to a range of densities or on samples compacted to 100 percent of the maximum dry density. If a range of densities are tested, typically three or more specimens are compacted to different densities in 6 inch diameter metal molds. Compacted densities range from about 95 percent (or lower) to 100 percent (or higher) of the maximum dry density. Maximum dry density should be determined for aggregates base by AASHTO T-180 (Method D). The variation in density is accomplished by varying the number of blows per layer used to compact the specimens. Generally about 10, 30 and 55 blows are used. If only the CBR value at the maximum density is required, several samples are compacted to approximately 100 percent of the maximum dry density. Specimens are then soaked in water for four days before testing.

A cylindrical piston about 2 inch in diameter is then pushed into the specimen at a rate of 0.05 inches per minute. Three typical CBR test force-penetration curves and necessary corrections are shown in Figure 2.9. The CBR value is calculated by dividing the force on the piston at 0.10-inch or 0.20-inch penetration by a standard reference load of 1,000 pounds or 1,500 pounds at penetrations of 0.1-inch or 0.2-inch, respectively. The CBR value is expressed as a percentage. CBR values range from 3 percent for poor subgrade soils to 100 percent or higher for high quality aggregates base.

Field In-Place CBR Test: Field in-place bearing ratio tests occasionally are used for evaluation and design when (1) the degree of saturation of the material to be evaluated is 80 percent or greater, (2) the material is coarse grained and cohesionless, or (3) the material has not been modified by construction activities during the two years preceding the test. The test is performed in accordance with ASTM D 4429. The test is most suitable for evaluation of the relative quality (bearing capacity) of subgrade soils, but is applicable to subbase and to some aggregates base course materials. Field in-place testing permits evaluation of the material in the condition that exists in the field at the time of testing. Subsequent treating, disturbing, handling, compaction or change in water content of the material invalidates the test results.

R-Value: The R-Value of a soil or aggregates base is the materials resistance value as measured in a stabilometer. The standard test method for this procedure is ASTM D 2844 (AASHTO T 190). In this procedure, a sample of soil or aggregates is compacted in a cylindrical 4-inch diameter mold to a height of approximately 2.5 inches. The sample is then placed in a rubber membrane inside the stabilometer. A vertical pressure of 160 psi is applied to the top of the specimen and the resulting horizontal pressure is measured and recorded. The vertical pressure is then decreased to 80 psi and the horizontal pressure is adjusted to 5 psi. A calibrated pump handle on the stabilometer is then turned at two turns per second to adjust the horizontal pressure from 5 psi to 100 psi and the number of turns recorded. The R value is calculated with the following equation:

$$R = 100 - \frac{100}{\frac{2.5}{D} \cdot \left(\frac{160}{P_h}\right) - 1 + 1}$$

where:

D = number of turns to increase horizontal pressure from 5 psi to 100 psi

P_h = horizontal pressure at a vertical pressure of 160 psi

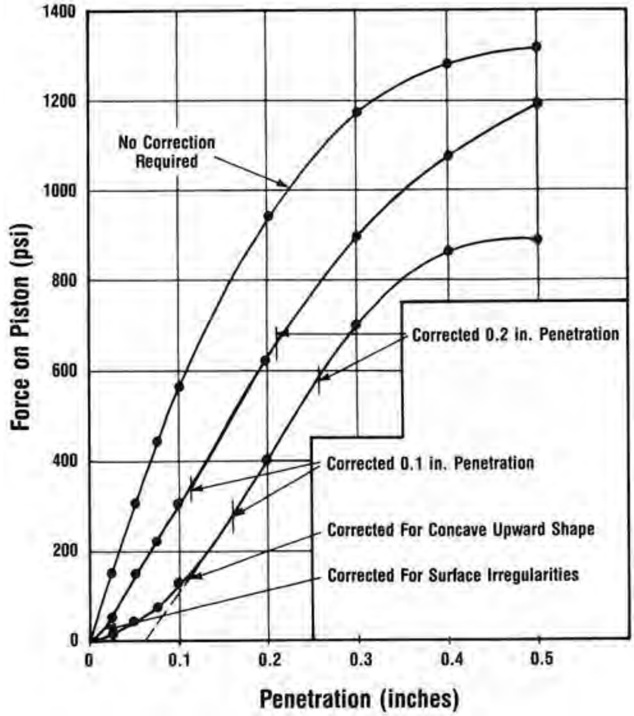


Figure 2.9 Load-penetration curves from CBR test (from Figure 3, ASTM D 1883)

Frictional Properties of Pavement Surfaces

The nature and mineralogy of the aggregates determine the friction properties of an exposed pavement surface. Surface friction characteristics are particularly important after aggregates are exposed due to wear and then subjected to critical conditions, including high traffic volumes and wet weather. The fine aggregates in portland cement concrete is important to the friction characteristics of the surface. For asphalt concrete, friction characteristics are influenced most by the coarse aggregates exposed at the surface. Figure 2.12 shows polished aggregates in asphalt concrete. Certain types of aggregates, which are structurally quite sound and are resistant to abrasion in the Los Angeles Degradation Test, become slippery when wet due to the polishing action of heavy traffic. Fine-grained limestone, which is highly soluble in acid, is generally susceptible to polishing and hence frequently is limited in use in pavement surface courses.

Methods of measuring the susceptibility of aggregates to polishing include the Insoluble Residue Test (ASTM D 3042) and several laboratory tests, discussed subsequently, that involve accelerated physical polishing of aggregates particles. In tests that use a laboratory polishing machine, aggregates either are included in a typical surface course mix or it is individually bonded to cement mortar or polyester resin panels. Aggregates with good to excellent resistance to polishing includes carbonate rock containing sand-sized impurities that are not dissolved in the insoluble residue test and other types of rock that contain a mixture of hard and soft minerals.


Courtesy of Strategic Highway Research Program

Figure 2.10 Example of polished aggregates in asphalt concrete pavement[26]

British Portable Pendulum Tester: The British Portable Pendulum Tester, AASHTO T-278 (ASTM E 303), can be used either in the laboratory or on actual pavement surfaces. The tester as illustrated in Figure 2.13, has a rubber slider attached to the end of a rigid pendulum. Pavements or specially prepared aggregates samples are tested by releasing the pendulum from a specified height and allowing the rubber slider to drag across the wet surface of the pavement or sample. The height to which the pendulum swings after contacting the test surface is measured on a special scale graduated in British Pendulum Numbers (BPN).

Accelerated Polishing Using British Wheel: The British Wheel Test, AASHTO T-279 (ASTM D 3319), provides a means of polishing aggregates particles in the laboratory and was originally devised in the Road Research Laboratory in the United Kingdom. The British Wheel Test is used as the basis of specification requirements in some states in the United States. The apparatus consists of a cylindrical road wheel of specified size and shape. Fourteen test specimens are clamped onto the periphery of the wheel to form a continuous curved surface of aggregates particles which is 1¾ inches wide and 16 inches in diameter. Specimens are prepared from aggregates passing the ½-inch sieve and retained on the ⅜-inch sieve. The aggregates particles are placed and cemented into curved molds in a single layer. The wheel, with specimens attached, is rotated against a standard rubber tire. Some agencies utilize a smooth rubber tire, others a rubber tire with a cross hatched tread pattern. Different results are obtained, depending on type of tire used. An abrasive and water are continuously fed to the surface of the test specimens. The tire is rotated at a speed of 320±5 rpm for 10 hours. Initial and final friction values are measured using the portable pendulum tester described previously.

Other Test Methods: Several other methods of testing the polishing potential of aggregates or wearing surface mixtures are listed in the Appendix located at the end of this chapter. Different agencies use different versions of polishing tests, but most rely upon a combination of field service performance and petrographic examination in selecting aggregates for surface course applications.

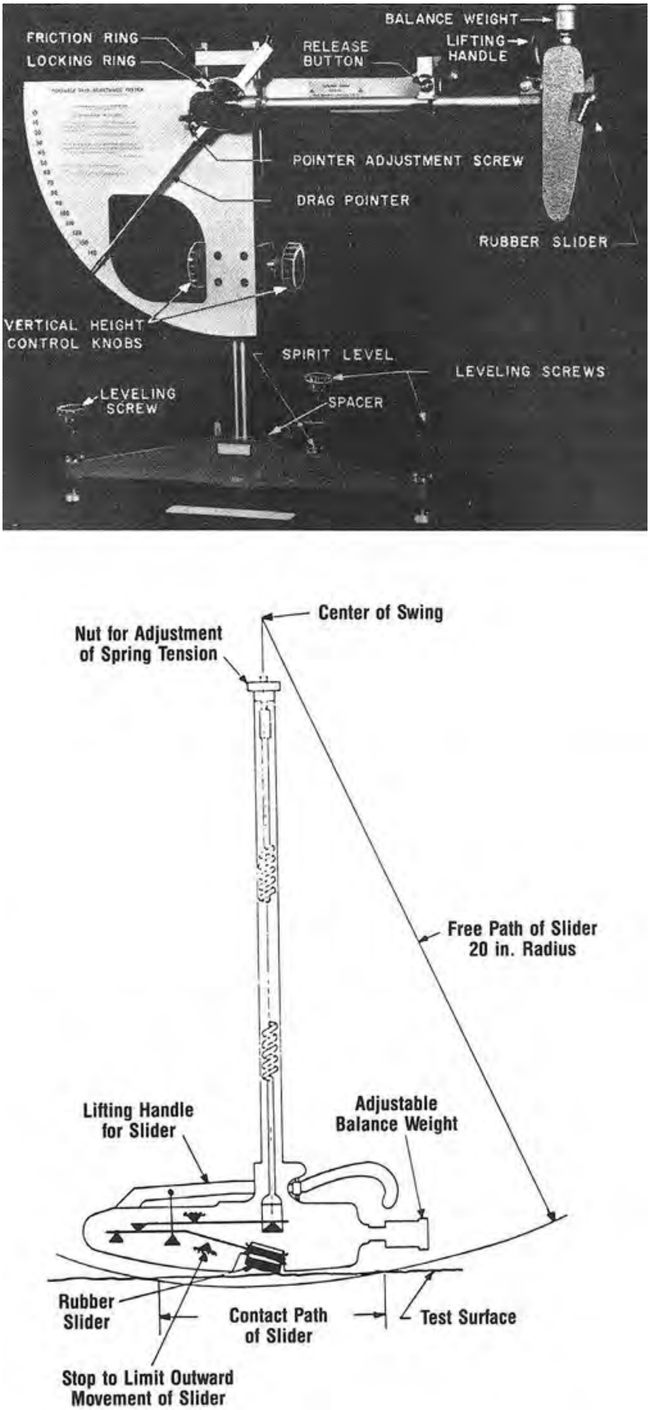


Figure 2.11 British portable pendulum tester (from ASTM E 303)

Alkali Aggregates Reactivity Testing in Concrete

Certain constituents in some aggregates can be reactive when combined with alkalies found in portland cement. In particular, certain types of silica found in some aggregates may react with alkalies in cement to create an Alkali Silica Reaction (ASR). Another type of reaction, Alkali Carbonate Reaction (ACR), can occur when alkalies react with certain carbonate aggregates. The resulting reaction of both ASR and ACR is expansion within the hardened concrete, which if severe enough, can cause cracking and deterioration. There are several test methods available to determine if an aggregates is potentially reactive with alkalies. One method that can be used for both ASR and ACR is ASTM C 295 which is a petrographic examination of the aggregates. In this method, an experienced petrographer uses various techniques to study the aggregates sample and determine the type and quantity of minerals present. Minerals that have the potential for either ASR or ACR are identified; however there is no attempt to determine if these minerals are actually reactive. If a petrographic examination identifies potentially reactive minerals, then more specific tests should be performed.

Alkali Silica Reaction: There are a variety of tests available to determine if aggregates may exhibit ASR. A listing of the most utilized tests is as follows:

ASTM C 227: This test method is performed by preparing a batch of mortar consisting of 1 part cement to 2.25 parts of a graded aggregates. The aggregates either can be a fine aggregates or a coarse aggregates sample that has been crushed. Both the coarse and the fine aggregates must be processed to meet a standard grading. The cement should have an alkali content of 0.8 percent or higher. The mortar is formed into 1 inch x 1 inch x 11¼ inch bars and cured for 24 hours. Upon completion of curing, an initial length measurement is made. The bars are then placed in containers where they are suspended over water and the container is placed in a 100° F environment. Subsequent length readings are taken at 14 days, for the first six months, and then at nine and 12 months. If an alkali silica reaction occurs, the expansion will be evident in the length readings. Expansions exceeding 0.05 percent at three months or 0.10 percent at six months may be indicative of ASR.

ASTM C1260: This test requires mortar bars of the same size and makeup as the bars in the ASTM C 227 test. The exception is that there is no requirement for the alkalinity of the cement. After forming, the bars are cured for 24 hours and then placed in water with a temperature of 176° F for another 24 hours. Upon removal from the water, an initial length measurement of the bars is made. The bars are then submerged in a solution of sodium hydroxide (1 N NaOH) and held at a temperature of 176° F. The sodium hydroxide and elevated temperature serve to speed up any potential alkali silica reaction. Three periodic readings and a final reading are taken over 14 days. Expansions greater than 0.20 percent at 14 days are considered potentially deleterious. Expansions less than 0.1 percent are considered innocuous. Expansions between 0.10 percent and 0.20 percent are considered inconclusive. Many of the ASR tests take from several months to a year to complete. The relatively short duration of this test makes it useful as quick screening test for potential ASR. The aggressive nature of this test should be taken into account. Aggregates showing potentially deleterious reactions warrant further testing with other procedures.

ASTM C 1567: This test follows the same procedure as ASTM C1260 but allows for the evaluation of the effectiveness of supplementary cementitious materials (SCM) in mitigating potential ASR. Aggregates exceeding the 0.1 percent expansion limit using ASTM C1260 can be tested using this procedure with a SCM to reduce the expansion to acceptable limits.

ASTM C 1293: This test is performed by preparing a batch of concrete using a high alkali cement, the aggregates to be evaluated, either coarse or fine and a control aggregates, either coarse or fine. The control aggregates must be shown to be non-reactive for either ASR or ACR. In addition to using a high alkali cement, the alkali level in the concrete mix is boosted by adding a prescribed amount of sodium hydroxide. Three concrete test bars measuring 3 inch x 3 inch x 11¼ inch are then molded and cured for 24 hours. Upon removal from the molds, an initial length reading of each bar is made. The bars are then placed in a container where they are suspended over water and stored in a 100° F environment. Subsequent length readings are made at 7, 28 and 56 days as well as three, six, nine and 12 months. Expansions equal to or greater than 0.04 percent at one year are considered to be potentially reactive.

ASTM C 289: This test is performed by reacting a 25-gram sample of dry #50 to #100 size aggregates in a solution of sodium hydroxide for 24 hours at 80° C. The amount of dissolved silica and the reduction in alkalinity of the solution are plotted on a standard curve. The location of the plotted point on the curve is used to determine of an aggregates is innocuous, deleterious or potentially deleterious. This test has been reported to have poor reliability and may give results that differ from mortar and concrete tests such as ASTM C 227, C 1260 and C 1293.[31]

Alkali Carbonate Reaction: There are several widely accepted test methods for determining if an aggregates is potentially deleterious with respect to ACR.

ASTM C 586: This test is used as a research and screening tool for aggregates to determine if it has the potential for ACR. It is performed by first preparing cylindrical aggregates samples measuring 35mm long by 9mm diameter or prismatic samples measuring 35 mm x 9mm x 9mm. The specimens are soaked in water and measured periodically until the change in length during a 24-hour period is less than 0.02 percent. At this point the initial length reading is recorded. The samples are then submerged in sodium hydroxide. Length readings are obtained at seven, 14, 21 and 28 days and then at four-week intervals up to one year. Expansions greater than 0.10 percent may indicate a deleterious reaction. This test is considered relatively severe; therefore, further testing with other procedures should be performed if a deleterious reaction is observed.

ASTM C 1105: This ACR test is performed by testing the aggregates in a concrete mixture to determine if a reaction occurs. The cement used can either be the "job cement" that will be used with the aggregates in actual field conditions, or a reference cement if the purpose of the test is to simply test the aggregates for general use. The mixture is molded into bars measuring 3 inches x 3 inches x 11.25 inches After curing, an initial length measurement of the bars is performed followed by storage in a 100 percent humidity moist room or cabinet at 73° F. Subsequent length measurements are made at seven, 28 and 56 days and three, six, nine and 12 months. An aggregates is considered to be potentially deleteriously reactive if expansion exceeds 0.015 percent at three months, 0.025 percent at six months or 0.030 percent at one year.

Aggregates Resistance to Moisture Induced Damage in Asphalt Mixtures

The resistance of compacted asphalt concrete mixtures to moisture-induced damage, frequently referred to as resistance to *stripping*, is determined by AASHTO Method T-283 and ASTM D 4867. In this test, specimens prepared with the specific aggregates and asphalt to be used in the field mixture are compacted into cylindrical specimens usually 4 inches in diameter and 2.5 inches high. These specimens are moisture conditioned by first saturating them with water under a vacuum, subjecting them to an optional freeze/thaw cycle and then soaking them in 140° F water for 24 hours . The specimens are then tested for indirect tensile strength and compared with the strength of duplicate specimens not subject to moisture conditioning.

The resistance of the asphalt specimen to moisture is influenced by the properties of the asphalt, the type and concentration of antistripping additives that may be used, the properties of the aggregates and environmental conditions. Stripping, which is the separation of the asphalt from the aggregates surface in the presence of moisture, is a serious problem influencing the durability of many asphalt concrete mixtures. Some aggregates have greater affinity for water than for asphalt; that is, it is hydrophilic or water-loving. In general, such aggregates is acidic in nature and has greater surface charge than hydrophobic aggregates. Quartz minerals, as found in granite, gravel and other siliceous aggregates, are typically hydrophilic. On the other hand, carbonate aggregates, like limestone, are usually hydrophobic or water-hating. Carbonate aggregates are basic in nature, possessing a positive surface charge and a much greater affinity for asphalt. Research continues toward the development of more reliable methods of predicting moisture damage to pavements as a result of stripping.[27]

Aggregates for Use as Structural Backfill

High quality fine or coarse aggregates often are used as a backfill material behind retaining walls or around utilities such as pipes. In these cases, many of the properties already discussed are often specified. Others properties that are often specified are resistivity and friction angle.

Resistivity: The resistivity test is used to determine if an aggregates or soil material is potentially corrosive to metal. Some retaining walls use metal straps to anchor the wall into the backfill material, therefore it is important that the backfill not cause corrosion in the straps. This is also important when aggregates are used as a backfill material around metal pipes. The electrical resistivity of soil or aggregates serves as an indicator of potential corrosiveness. Soils or aggregates containing high levels of corrosive materials such as salts or chlorides will have low resistivity values; therefore, a minimum resistivity is often specified.

Two laboratory test methods for measuring resistivity in soils are AASHTO T 288 and ASTM G187. In each of these methods, the soil or aggregates are compacted by hand into a "soil box." The soil box utilized in AASHTO T-188 is a box of specified dimensions and restricts the particle size tested to material passing the 2.00-mm (#10) sieve. The soils box utilized in ASTM G-187 is capable of being adjusted in order to evaluate particles of different sizes. Both soil boxes are typically made of a non-conducting material such as polycarbonate plastic. Two of the interior, opposing walls in the soil box are covered with stainless steel sheets that serve as electrodes. After the soil or aggregates have been placed in the soil box, an electrical current is passed between the two electrodes and the resistance of the soil or aggregates sample in ohms is measured. With the dimensions of the soil box, the resistivity in ohm-cm can be calculated for the soil or aggregates sample. The AASHTO T 288 method is used to determine the minimum resistivity of the sample by increasing the moisture content of the sample until a minimum resistivity is determined. The ASTM G 187 method allows for the determination of resistivity at 100 percent saturation, as specified in many Mechanically Stabilized Earth Wall applications.

While a high resistivity is required to inhibit corrosion, in some cases, a relatively low resistivity is desirable. A low resistivity may be required if an aggregates source is to be used as an electrical grounding material. This often is the case when aggregates are used as ground cover at electrical substations and other power facilities. In these cases, it is desirable for the aggregates to be able to adequately transfer current into the surrounding ground.

Friction Angle: To properly design a retaining wall, it is necessary to know the internal friction angle of the backfill material. This typically is determined on soils or fine aggregates using either a direct shear test or a triaxial shear test.

The direct shear test is performed in accordance with ASTM D 3080 (AASHTO T 236). In this method, a sample is compacted to a specified percentage of maximum dry density into a cylindrical or square shear box. The box is split horizontally so that the top half of the box can move independently of the bottom half. A force is applied normal to the sample and a shear force is applied to the box by moving one half relative to the other. The shear force required to cause failure in the sample is recorded. This test is repeated using different normal forces. The shear force versus normal force is then plotted and the friction angle determined from the slope of the plotted line.

A triaxial compression test also can be performed to determine shear strength and friction angle. There are several types of triaxial tests that can be performed. In each test, a sample of soil or aggregates is compacted to a specified density in a cylindrical mold with a height to diameter ratio of at least 2:1. The sample is then enclosed in a rubber membrane and placed in a triaxial cell. The triaxial cell usually is a cylindrical chamber that can be pressurized thereby giving an all around confining pressure to the sample. This simulates the confining pressure that would be applied to the material in service in the field. A slow compressive axial stress is then applied to the top of the specimen until failure occurs. The confining pressure and axial stress at failure can be used to calculate the shear stress at failure. The results from several tests at different confining pressures can be plotted and a friction angle determined from the plot. There are several triaxial methods that can be performed. ASTM D 2850 is an unconsolidated, undrained test which means that as the confining pressure is applied to the sample and the axial load is applied, the sample itself is not allowed to drain and release pressure. ASTM D 4767 (AASHTO T 297) is a consolidated, undrained test, which means that the sample is allowed to drain and release pressure and consolidate while the confining pressure is applied. Once the pressure inside the sample stabilizes, the drain valve is closed and the axial load is applied.

2.6 Blending of Aggregates

Frequently two or more aggregates gradings must be combined to meet a given end-use specification. The percent by weight of each aggregates grading necessary to meet the required specification is obtained by use of either analytical or graphical procedures.

Analytical Procedure

The analytical procedure for determining proportions of different types of aggregates to be combined to produce the required aggregates blend are complicated and time-consuming when solved by hand, but are easily accomplished using a computer. The analytical method normally yields only one of several possible combinations and hence a trial and error procedure is required to optimize the blend.

Trial and Error Method: The basic equation for expressing the combination of two or more types of aggregates is given below:

$$P = A \cdot a + B \cdot b + C \cdot c + \ldots \tag{2-12}$$

where:

P = Percentage of the combined aggregates (A + B + C + etc.) passing a given sieve size

A, B, C, ... = Percentage of each aggregates (A,B,C, etc.) that passes a given sieve size

a, b, c, ... = Proportion of each aggregates needed to meet the requirements for material passing the given sieve where a+b+c+... = 1.00.

The analytical procedure using equation (2-12) is a *trial and error* one. In this procedure, a trial blend is selected based on (1) experience, (2) plots of each aggregates grading and (3) the blend specification. The procedure involves selection of a critical sieve and then determination of the proportion a, b, c, etc. of each aggregates, which permit the resulting aggregates blend to meet the specification for the *critical sieve*. The critical sieve is usually taken as that sieve having a blend specification of 50 ± 10 percent passing it.

Example Problem: Two aggregates gradings are tabulated in Table 2.5. Also given on the last line of this table is the specification requirement for the desired product to be obtained by blending the two types of aggregates. The grading data show that neither aggregates A nor B when used alone meets the specification requirement. Therefore, a blend must be used of the two aggregates gradings. A trial blend is determined by substituting the relationship a = 1 - b (recall that a + b = 1) into equation (2-12) and rearranging the equation so as to group together the only unknown which is b:

$$P = A[1 - b] + B \cdot b \qquad (2\text{-}13a)$$

$$P = A - A\sum b + B \cdot b \qquad (2\text{-}13b)$$

$$P - A = [B - A] \cdot b \qquad (2\text{-}13c)$$

$$P = A - Agb + Bgb$$

Now solve equation (2-13c) for b giving:

$$b = \frac{P - A}{B - A} \qquad (2\text{-}13d)$$

Table 2.5 Grading Data for Two Aggregates (Percent Passing)[29]

Material	2 in.	1-½ in.	¾ in.	No. 4	No. 10	No. 200
Aggregate A	100	100	63	25	15	3
Aggregate B	100	95	85	50	36	7
Specification of Blend	100	90-100	65-80	30-45	20-35	0-5

For this example use the No. 4 sieve as the critical one since it is reasonably close to the size for which 50 percent is finer. Let the desired percent passing (P) of the blend be midrange:

$$b = (37.5 - 25)/(50 - 25) = 0.5$$

Since b = 0.5, an equal proportion of aggregates A and aggregates B is required (i.e. use a 50-50 blend).

The initial proportions determined for the critical sieve must then be checked for all sieves in the specification. Adjustments to the proportions are made as necessary to ensure that the percentages of the blend for all sieves are within the required specification.

The first trial described above gives a 50-50 blend that is within the specification. The upper limit for the No. 200 sieve, however, is 5 percent, which is exactly the upper allowable limit. The upper limit is calculated by using equation (2-13a) and the values of b = 0.5 and a = 1-b = 0.5.

$$P = 0.5\ (3\%) + 0.5\ (7\%) = 5\%.$$

Second Trial: The proportion of aggregates B must be reduced to move the combined grading away from the upper specification limit. However, the data calculated to check the 50-50 blend proportion, which are not shown, also indicate that the reduction in the proportion of aggregates B is limited by the No. 10 sieve. The limit on the No. 10 sieve occurs since the grading of the blend, which is 25.5 percent, is near the lower limit of the required specification. For the second trial, try a = 0.6 and b = 0.4 and repeat the check calculations for all sieves.

The second trial also is within the specifications and is better than the first trial. However, the grading of the resulting blend is near the specification limits on the 1½ inch, No. 10 and No. 200 sieves. Additional trials are therefore required to fine-tune the proportions.

Although the analytical procedure just described appears to be complex and time-consuming, in reality it is not. Successive trials are accomplished easily and quickly using a computer and currently available software.

Graphical Procedure

Graphical procedures exist for blending multiple aggregates gradations.[29] Only the graphical procedure for blending two types of aggregates are described in this handbook. The graphical procedure for blending two gradings is relatively easy and permits determination of all possible proportions of the two gradings that meet the required specification. The resulting information permits the user to exercise any one of multiple options to produce an optimum and economical blend of the two gradings that fall within the required specification.

The graphical procedure is based on the same basic relationship as the trial and error procedure, but utilizes graphical rather than analytical techniques. The procedure provides a one-sheet pictorial view of the blending process. For blending two gradings, the graphical procedure is straightforward and direct.

Example Problem: To illustrate the procedure, the grading data and specification given previously in Table 2.5 is used[29]. The graph employed in this procedure is given in Figure 2.14a. The graph has a vertical percentage passing scale for each of the two gradings to be combined ranging from 0 percent to 100 percent and also two horizontal scales that show the proportions of each aggregates in the blend.

The grading of aggregates A is plotted on the 100 percent A vertical scale, given on the left side of the graph; the grading of aggregates B is plotted on the 100 percent B (0 percent A) vertical scale given on the right side of the graph. The grading data for each aggregates from Table 2.5 is plotted in Figure 2.14a to illustrate this step of the procedure. Points on the vertical scales that are common to the same sieve size are then connected by a straight line and the line is labeled as illustrated in Figure 2.14b. The line connecting the two points for each sieve contains all possible percentages of that size for any blend of aggregates A and aggregates B. A vertical line drawn within the graph and intersecting a sieve line gives a blend of aggregates A and aggregates B, as measured from the top and bottom horizontal scales, respectively, with a percentage passing that sieve that is indicated by either vertical scale at the point of intersection of the sieve line with the vertical line.

Next, the upper and lower specification limits for each sieve size are plotted on each sieve line as illustrated in Figure 2.14c. The zone of the graph that exists between the two points that are plotted for each sieve line represents all proportions of aggregates A and aggregates B that meet the specification requirements for that sieve. When all specification limits for all sieves have been plotted on the graph, the plotted points for the lower limits of consecutive sieves are connected and the plotted points for the upper limits of connective sieves are connected; dashed lines are used in Figure 2.14c.

If the two aggregates can be blended to meet the required specification, a vertical zone lying inside the specification limits will be defined on the graphical plot and the controlling sieve size for the upper specification limit and that for the lower specification limit will also be depicted. This zone for the illustrative example is shown cross- hatched in Figure 2.14d. The vertical zone is a specification envelope that contains all possible blends of aggregates A and aggregates B that meet the specification requirements for all sieves.

In the example given, 50 percent to 76 percent of aggregates A and 24 percent to 500 of aggregates B, respectively, meet the specification when blended. The controlling sieve for the upper limits is the No. 200 sieve and the No. 10 sieve controls the lower limits.

If the dashed lines connecting the upper and the lower specification limits do not permit establishment of a defined vertical zone which does not cross a dashed line, the two types of aggregates cannot be blended to meet the existing specification. In this case, a third aggregates must be obtained and this aggregates must be blended with either aggregates A or B, or with both aggregates A and B.

Computerized Aggregates Blending Programs

The blending of two or more aggregates sizes or different materials frequently is required to meet grading or quality specifications. Although the calculations are relatively easy, the repetition and number of calculations can be cumbersome and time consuming. Most engineers and technicians use a computerized blending program. These are generally simple spreadsheets that easily can be created on standard spreadsheet software, but there are also commercially available programs.

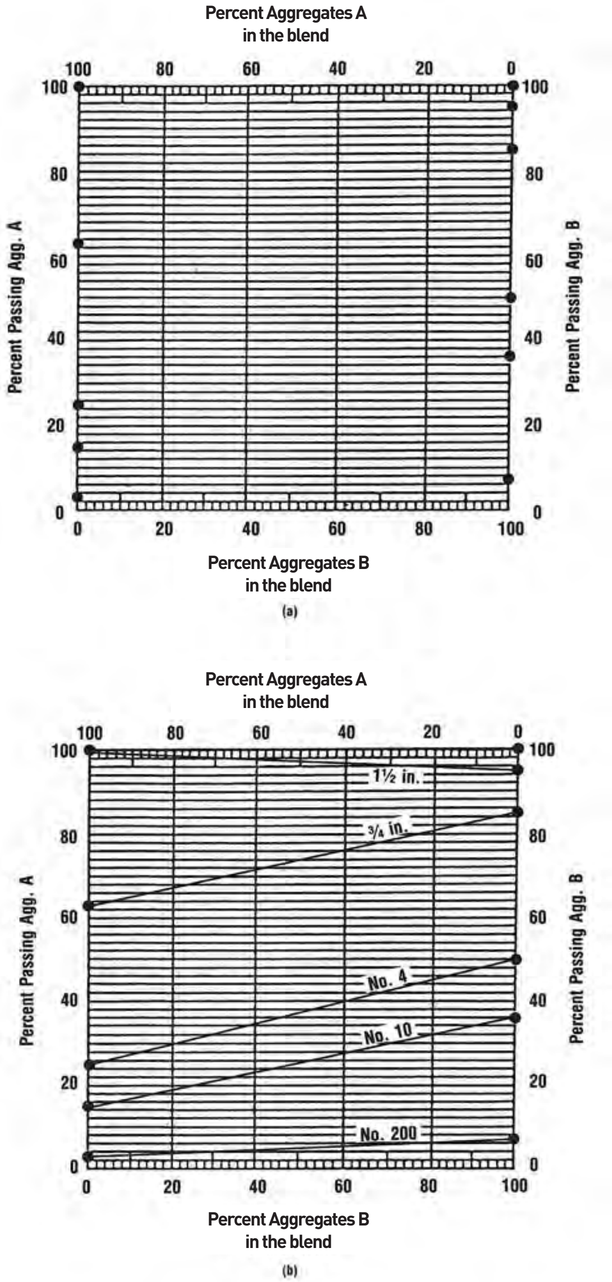
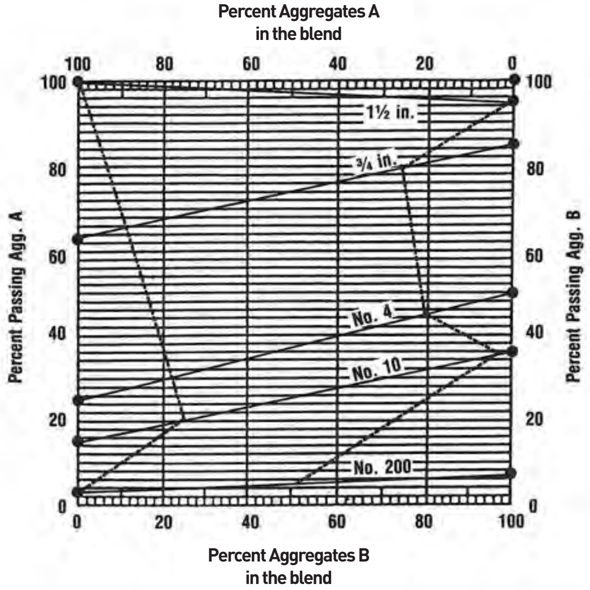
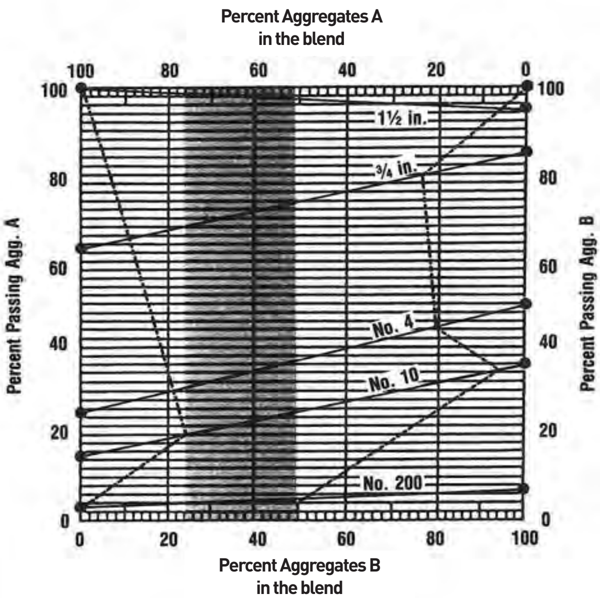


Figure 2.12 Graphical procedure for blending of two aggregates gradings (Figure 2.14 (d) adapted from Reference 29)


Percent Aggregates A in the blend
100
80
60
40
20
0
Percent Passing Agg. A
Percent Passing Agg. B
1½ in.
¾ in.
No. 4
No. 10
No. 200
Percent Aggregates B in the blend

(c)


Percent Aggregates A in the blend
100
80
60
40
20
0
Percent Passing Agg. A
Percent Passing Agg. B
1½ in.
¾ in.
No. 4
No. 10
No. 200
Percent Aggregates B in the blend

(d)

Summary

The choice of aggregates for use in various end products can be based on results from the many tests described in this chapter, tests referenced in the Appendix to this chapter, or tests described elsewhere. Historical records of aggregates performance in prior service of a similar nature to that under consideration also should be taken into account. The highest quality aggregates that is economically available should always be chosen for all applications. Finally, standard specifications for aggregates should be based on[28] *"test limits considered the most liberal that may safely be allowed . . . with the understanding that where higher grade materials are locally available, more rigid requirements should be inserted."*

APPENDIX

ASTM and AASHTO Standards for Aggregates

ASTM

The American Society for Testing and Materials (ASTM) is recognized worldwide as a nonprofit organization whose membership is composed of representative users, producers and general interest groups. The organization's purpose is the development of voluntary consensus standards for materials, products, systems and services. ASTM develops both standard specifications and standard methods of test needed to ensure compliance with them. ASTM standards are published in 65 individual volumes covering a wide variety of materials. Many of them are available as separate reprints. Those related to aggregates are found among the several volumes designated as Section 4, Construction Materials and Practices.[30]

AASHTO

The American Association of State Highway and Transportation Officials (AASHTO) is a similar group to ASTM which represents the highway or transportation departments from each of the 50 states, the District of Columbia, Puerto Rico and the U.S. Department of Transportation. AASHTO also develops both specifications and test methods, many of which are adopted from ASTM standards. Specification limits generally are set to be as liberal as may be safely allowed. AASHTO standards are contained in a two-volume set entitled AASHTO Materials, Part I Specifications and Part II Tests.[28]

Listing of Available AASHTO and ASTM Specifications

The following is a listing of available AASHTO and ASTM Specifications which involve aggregates:

1. Aggregates Base and Subbase and Soil-Aggregates:
   - AASHTO M-283 Coarse Aggregates for Highway and Airport Construction
   - ASTM D 2940 Graded Aggregates for Bases or Subbases
   - AASHTO M-147 Materials for Aggregates and Soil-Aggregates Subbase, Base and Surface Courses (similar to ASTM D 1241)
   - AASHTO M-155 Granular Material to Control Pumping Under Concrete Pavement.

2. Aggregates for Bituminous Paving Applications:
   - AASHTO M-43 (ASTM C 448) Standard Sizes of Coarse Aggregates
   - AASHTO M-29 (ASTM D 1073) Fine Aggregates for Bituminous Paving Mixtures
   - ASTM D 692 Coarse Aggregates for Bituminous Paving Mixtures
   - AASHTO M-17 (ASTM D 242) Mineral Filler for Bituminous Paving Mixtures
   - AASHTO R-12 Bituminous Mixture Design Using Marshall and Hveem Procedures (also see Asphalt Institute Publication MS-2)
   - ASTM D 3515 Hot-Mixed, Hot-Laid Bituminous Paving Mixtures (includes aggregates specifications for Open Graded Mixtures)
   - ASTM D 693 Crushed Aggregates for Macadam Pavements
   - ASTM D 1139 Crushed Stone, Crushed Slag and Gravel for Bituminous Surface Treatments

3. Aggregates for Portland Cement Concrete:
   - AASHTO M-6 Fine Aggregates for PC Concrete
   - AASHTO M-80 Coarse Aggregates for PC Concrete
   - ASTM C 33 Concrete Aggregates (fine and coarse)
   - AASHTO M-195 (ASTM C 330) Lightweight Aggregates for Structural Concrete

4. Practices-General:
   - AASHTO R-1 (ASTM E 380) Metric Practice Guide
   - AASHTO R-10 Definitions of Terms for Specifications and Procedures
   - AASHTO R-11 (ASTM E 29) Practice for Indicating Which Places of Figures are to bwe Considered Significant in Specified Limiting Values
   - AASHTO M-145 The Classification of Soils and Soil-Aggregates, Fill Materials and Base Materials
   - AASHTO M-146 Terms Related to Subgrade, Soil-Aggregates and Fill Materials
   - ASTM D 8 Definitions of Terms Relating to Materials for Roads and Pavements
   - ASTM C 125 Terminology Relating to Concrete and Concrete Aggregates
   - ASTM D 3665 Random Sampling of Construction Materials

Listing of Available AASHTO and ASTM Test Procedures

The following AASHTO and ASTM standard test methods are listed by title to serve as an aid in helping to locate appropriate test methods. A large number of standards have been developed over the years by the two major organizations involved. Other organizations which have standard test methods include the state transportation agencies, federal government agencies and various related industries. A complete listing of all such standards is beyond the scope of this Handbook.

1. General Testing:
   - AASHTO M-92 (ASTM E 11) Wire Cloth Sieves for Testing Purposes
   - AASHTO M-231 Weights and Balances Used in Testing
   - ASTM Manual of Aggregates and Concrete Testing (found in ASTM Volume 04.02 in the back of the gray pages)
   - AASHTO R 18 Establishing and Implementing a System for Construction Materials Testing Laboratories
   - ASTM D 3666 Evaluation of Inspecting and Testing Agencies for Bituminous Paving Materials
   - ASTM C 1077 Practice for Laboratories Testing Concrete and Concrete Aggregates

2. Sampling and Sample Preparation:
   - AASHTO T-2 (ASTM D 75) Sampling Aggregates
   - AASHTO T-248 (ASTM C 702) Reducing Field Samples of Aggregates to Testing Size
   - AASHTO T-87 (ASTM D 421) Dry Preparation of Disturbed Soil and Soil Aggregates Samples for Tests
   - AASHTO T-146 Wet Preparation of Disturbed Soil Samples for Tests

3. Particle Size Analysis of Aggregates:
   - AASHTO T-27 (ASTM C 136) Sieve Analysis of Fine and Coarse Aggregates
   - AASHTO T-11 (ASTM C 117) Amount of Material Finer Than the No. 200 Sieve
   - AASHTO T-30 (ASTM D 5444) Mechanical Analysis of Extracted Aggregates
   - AASHTO T-88 (ASTM D 422) Particle Size Analysis of Soils
   - AASHTO T-37 (ASTM D 546) Sieve Analysis of Mineral Filler

4. Properties of Fines in Aggregates:
   - AASHTO T-176 (ASTM D 2419) Sand Equivalent Test for Plastic Fines in Graded Aggregates and Soils
   - ASTM D 4318 (Combines AASHTO T-89 and T-90) Liquid Limit, Plastic Limit and Plasticity Index of Soils
   - AASHTO T-210 (ASTM D 3744) Aggregates Durability Index
   - AASHTO T 330 Standard Method of Test for The Qualitative Detection of Harmful Clays of the Smectite Group in Aggregates Using Methylene Blue

5. Tests to Evaluate General Quality of Aggregates (unconfined or in concrete):
   - AASHTO T-104 (ASTM C 88) Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
   - AASHTO T-103 Soundness of Aggregates by Freezing and Thawing
   - ASTM D 4792 Potential Expansion of Aggregates from Hydration Reactions
   - AASHTO T-161 (ASTM C 666) Resistance of Concrete to Rapid Freezing and Thawing
   - AASHTO T-96 (ASTM C 131 or C 535) Resistance to Abrasion (Degradation by Abrasion and Impact) of Small or Large Size Coarse Aggregates by Use of the Los Angeles Machine
   - ASTM D 6928 (AASHTO T 327) Resistance of Coarse Aggregates to Degradation by Abrasion in the Micro-Deval Apparatus
   - ASTM D 7428 Standard Test Method for Resistance of Fine Aggregates to Degradation by Abrasion in the Micro-Deval Apparatus
   - ASTM D 4791 Flat or Elongated Particles in Coarse Aggregates

6. Deleterious Materials in Aggregates:
   - AASHTO T-21 (ASTM C 40) Organic Impurities in Sands for Concrete
   - AASHTO T-71 (ASTM C 87) Effect of Organic Impurities in Fine Aggregates on Strength of Mortar
   - AASHTO T-112 (ASTM C 142) Clay Lumps and Friable Particles in Aggregates
   - AASHTO T-113 (ASTM C 123) Lightweight Pieces in Aggregates
   - ASTM C 294 Nomenclature of Constituents of Natural Mineral Aggregates
   - ASTM C 295 Practice for Petrographic Examination of Aggregates for Concrete

7. Test to Evaluate Potential Alkali-Aggregates Reactivity
   - ASTM C 227 Alkali Reactivity Potential of Cement-Aggregates Combinations
   - ASTM C 289 Potential Reactivity of Aggregates (chemical method)
   - ASTM C 586 Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (rock cylinder method)
   - ASTM C 441 Mineral Admixture Effectiveness in Preventing Excessive Expansion Due to Alkali Aggregates Reaction
   - ASTM C 1260 Potential Alkali Reactivity in Aggregates (Mortar Bar Method)
   - ASTM C 1293 Determination of Length Change of Concrete Due to Alkali-Silica Reaction
   - ASTM C 1105 Length Change of Concrete Due to Alkali-Carbonate Reaction
   - ASTM C 1567 Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregates

8. Testing Aggregates in Bituminous Applications:
   - AASHTO T-165 (ASTM D 1075) Effect of Water on Cohesion of Compacted Bituminous Mixtures
   - AASHTO T-182 Coating and Stripping of Bitumen-Aggregates Mixtures
   - AASHTO T-195 (ASTM D 2489) Determining Degree of Particle Coating of Bituminous Aggregates Mixtures
   - AASHTO T-283 (ASTM D 4867) Resistance of Compacted Bituminous Mixture to Moisture Induced Damage
   - ASTM D 4469 Calculating Percent Absorption by the Aggregates in an Asphalt Pavement Mixture
   - ASTM D 6927 Resistance to Plastic Flow-Marshall Apparatus
   - ASTM D 1560 Deformation and Cohesion-Hveem Apparatus

9. Aggregates Base Moisture-Density-Permeability Relationships:
   - AASHTO T-99 (ASTM D 698) Moisture-Density Relationship Using a 5.5 Pound Rammer and a 12 Inch Drop
   - AASHTO T-180 (ASTM D 1557) Moisture-Density Relationship Using a 10 Pound Rammer and an 18 Inch Drop
   - AASHTO T-215 (ASTM D 2434) Permeability of Granular Soils (Constant Head)
   - AASHTO T-224 (ASTM D 4718) Correction for Coarse Particles in Soil Compaction Tests
   - ASTM D 2922 Density of Soil and Soil Aggregates In-Place by Nuclear Methods (shallow depth, both backscatter and direct transmission methods)
   - ASTM D 3017 Moisture Content of Soil and Soil Aggregates In Place by Nuclear Methods (shallow depth, back-scatter method only)
   - ASTM D 4253 Index Density of Soils Using a Vibratory Table (applicable to cohesionless, free-draining soils or soil aggregates)
   - ASTM D 4254 Minimum Index Density and Unit Weight of Soils
   - ASTM D 6938 (AASHTO T 310) Density and Water Content of Soil and Soil Aggregates by Nuclear Method (Shallow Depth)
   - AASHTO T-191 (ASTM D 1556) Density of Soil In-Place by the Sand Cone Method
   - ASTM D 2167 Density of Soil In-Place by the Rubber Balloon Method

10. Strength Parameters of Aggregates Base:
    - AASHTO T-190 (ASTM D 2844) Resistance R-Value and Expansion Pressure of Compacted Soils
    - AASHTO T-193 (ASTM D 1883) The California Bearing Ratio
    - AASHTO T 296 (ASTM D 2850) Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils
    - AASHTO T-212 (ASTM D 3397) Triaxial Classification of Base Materials, Soils and Soil Mixtures (Texas method, static loading, discontinued as a standard 1989)
    - AASHTO T 236 (ASTM D 3080) Direct Shear of Soils Under Consolidated-Undrained Conditions
    - AASHTO T 297 (ASTM D 4767) Consolidated-Undrained Triaxial Compression Test on Cohesive Soils
    - AASHTO T 307 Resilient Modulus of Soils and Aggregates Materials
    - ASTM D 6758 Stiffness of Soil and Soil-Aggregates by the Soil Stiffness Gauge

11. Specific Gravity, Absorption and Unit Weight of Aggregates:
    - AASHTO T-84 (ASTM C 128) Specific Gravity and Absorption of Fine Aggregates
    - AASHTO T-85 (ASTM C 127) Specific Gravity and Absorption of Coarse Aggregates
    - AASHTO T-19 (ASTM C 29) Unit Weight and Voids in Aggregates
    - ASTM D 7172 Relative Density (Specific Gravity) and Absorption of Fine Aggregates Using Infrared

12. Frictional Properties of Aggregates and Pavements:
    - AASHTO T-242 (ASTM E 274) Frictional Properties of Paved Surfaces Using a Full-Scale Tire (skid trailers)
    - AASHTO T-279 (ASTM D 3319) Accelerated Polishing of Aggregates Using the British Wheel
    - AASHTO T-278 (ASTM E 303) Measuring Surface Frictional Properties Using the British Pendulum Tester (BPT)
    - ASTM D 3042 Insoluble Residue in Carbonate Aggregates
    - ASTM E 707 Skid Resistance of Paved Surfaces Using the NC State Variable-Speed Friction Tester
    - ASTM E 660 Accelerated Polishing of Aggregates or Pavement Surfaces Using a Small-Wheel Circular Polishing Machine

13. Measurements and Indices of Particle Shape and Texture:
    - ASTM D 1252 (AASHTO T 304) Uncompacted Void Content of Fine Aggregates
    - ASTM D 4791 Flat or Elongated Particles in Coarse Aggregates
    - ASTM D 3398 Index of Aggregates Particle Shape and Texture
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Chapter 3
Geology and Exploration

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3.1 Introduction

This chapter is to be used as a guide to understanding the occurrence, chemistry and weathering of rock materials primarily as they relate to locating, testing and evaluating mineral aggregates resources. The chapter also is intended to serve as a guide for the exploration and evaluation of aggregates resources as well as a reference for management to facilitate understanding maps and reports on aggregates resources. Aggregates quality, as related to weathering of aggregates and aggregates reserves, is discussed in some detail because this knowledge is difficult to locate in the technical literature. Because a single chapter cannot fully cover all topics, numerous references are given for the reader who wishes to pursue this topic in greater depth.

3.2 The Occurrence of Natural Aggregates Resources

Sand and Gravel

Introduction: Deposits of sand and gravel, which are unconsolidated sedimentary materials, often are important sources of mineral aggregates. High quality natural sand and gravel occurring within economic marketing distance of urban areas often are critical in the construction of facilities such as roadways, plants, commercial buildings and residencies. A map that shows the location of major sand and gravel deposits in the United States is given elsewhere[1]. Because clean (i.e., not having any significant clay and silt) sand and gravel usually are deposited from water, sand and gravel deposits generally are found in valleys or in coastal plains.

Sand and gravel are concentrated because of the action of water, ice or wind. Such concentration usually results in relatively smooth, round particles. If the deposits formed are of suitable size, gradation and quality, they can be processed to conform to the requirements for various commercial aggregates. Generally, the coarser deposits (i.e., rich in particles greater in size than ¼ inch) are best because coarser sizes can be crushed to smaller sizes. A producer therefore has the flexibility by crushing of meeting different grain size distribution (i.e., gradation) requirements and of improving the angularity of individual particles. For this reason clay, silt or pure fine sand deposits usually have little value as aggregates but are mined for other purposes.

Committee of the Geological Society of America

Figure 3.1 Distribution of the Pleistocene glaciers in the United States

Glacial Deposits: Continental and alpine glaciers. Up to about 10,000 years ago, continental glaciers or ice sheets covered much of the northern portion of the Northern Hemisphere while simultaneously alpine glaciers occupied higher mountain areas to the south as illustrated in Figure 3.1. Ice sheets extended as far south as northern Pennsylvania in the Eastern United States, as far south as southern Indiana in the Mississippi Valley, and into northern Washington and Montana in the Western states. Glacial deposits consist of two broad categories: those deposited directly from moving ice, and those deposited by water running on, along, under or out from ice. Sand and gravel deposited from water associated with ice constitute most of the economic sand and gravel deposits found in glaciated areas. Figure 3.2 depicts the origin of continental glacial deposits that are typical of the hilly to mountainous Northeastern United States. Figure 3.3 shows the origins of continental glacial deposits that are typical of the Midwestern United States.

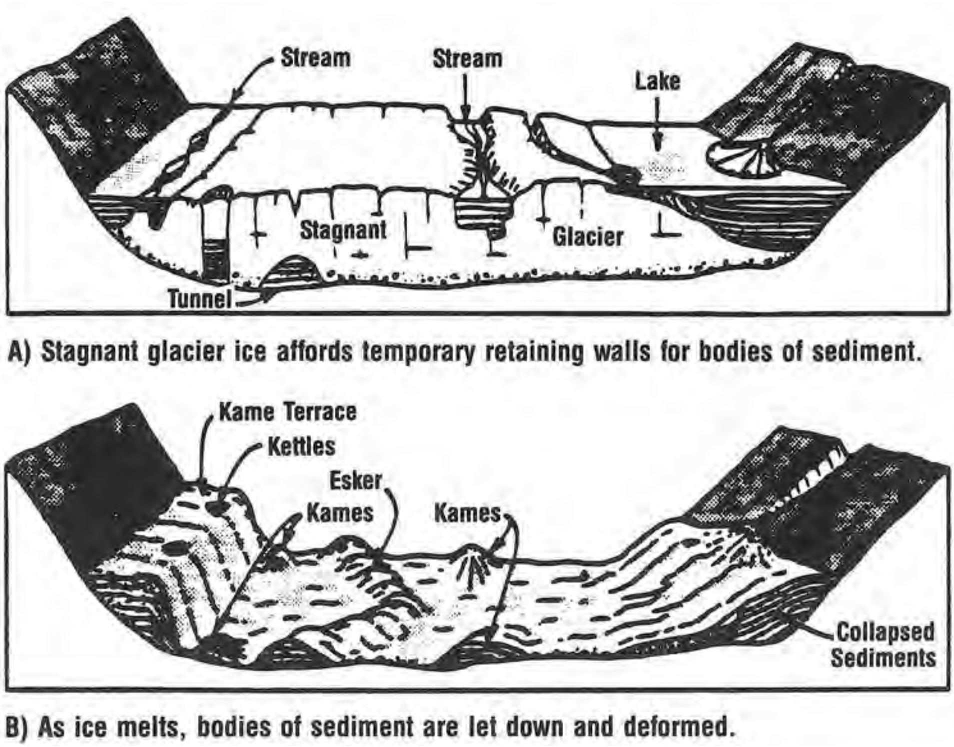
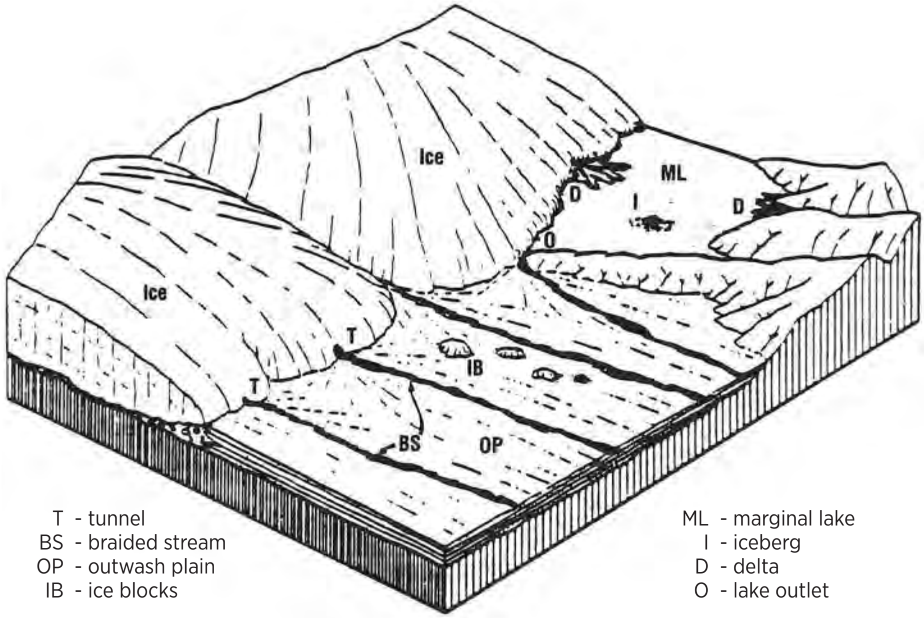


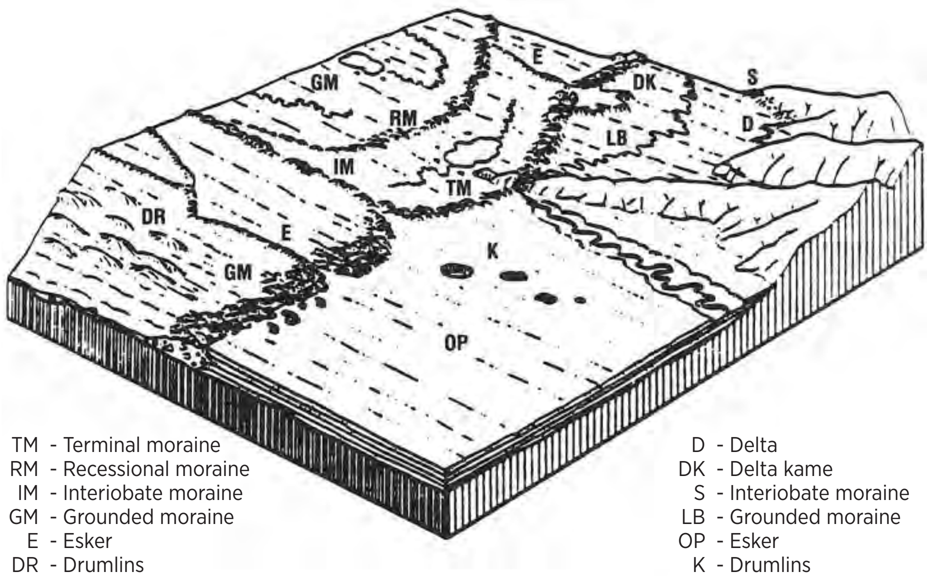
Figure 3.2 Origin of bodies of ice-contact stratified drift.[2]

- *Lodgement Till.* Sediment plastered on the ground or on knobs directly from the ice without reworking by water is called lodgement till. The latter forms, if rounded, are called *drumlins*. Lodgement till is unstratified and is not an economic source of sand and gravel because it contains too much clay-size ground-up rock that cannot economically be cleaned from the sand and gravel. Some lodgement till also contains excessively large blocks of rock that are costly to handle. Lodgement till, however, may provide a good source of material for projects requiring large quantities of fill.

- *Eskers* are long, sinuous landforms that were deposited as poorly stratified sand and gravel in stream channels under or on ice sheets. Eskers typically vary in length from 300 feet to 300 miles and can be up to 600 feet high. These deposits can be major sources of sand and gravel aggregates.



A. With the ice front stabalized and the ice in a wasting, stagnant condition, various depositional features are built by meltwaters.



B. After the ice has wasted completely away, a variety of new landforms made under the ice is exposed to view.

Figure 3.3 Marginal Landforms of Continental Glaciers.[3]

- *Kames* are irregular sand and gravel accumulations deposited by water running alongside, within or on ice. Kames are found as shoulders often at a constant elevation at the edges of valleys in which melting ice once lay. Kames also can be irregular hills that were pockets of sand and gravel within ice masses. At times, kames occur with eskers and either type of deposit can grade into deltas that form in ponded glacial lakes. All of these deposits may be economic sources of sand and gravel.

- *Outwash deposits.* Major stream channels (or sluiceways) come from melting continental ice sheets. These channels often are filled with significant economic sand and gravel accumulations. Outwash plains are relatively flat areas thinly covered with sand and gravel that were deposited in front of melting ice.

- *Continental ice terminal moraines.* Terminal moraines are located at the southernmost limit of continental ice sheets. These moraines were formed as the ice front started to retreat because of melting. Major economic accumulations of sand and gravel are found in some terminal moraine areas.

- *Alpine lateral and terminal moraines.* Sand and gravel deposited alongside or in front of alpine glaciers are lateral and terminal moraines, respectively. These moraines are found in high mountain valleys of the Western United States and are very bouldery and poorly stratified.

Marine Deposits: Marine deposits are formed where streams empty into the sea forming deltas and along the shores of continents and islands. Many of the major conglomerate, sandstone and shale formations originated from marine processes.

- *Beach and bar deposits.* Sand and gravel are deposited from wave and current action as *beaches and bars*. Lagoon deposits, which are typically organic silt and clay, are largely formed in bays behind offshore sand bars along coastal plains. They also can be found beneath beach sand deposits. The mineral and rock grains of beach deposits are much more uniform in size than glacial deposits. Relatively homogeneous beach-formed strata may blanket thousands of square miles. Generally, beach sand is rich in quartz. In some marine areas, however, the sand contains abundant seashells and coral particles. This sand, in some tropical areas, consists almost entirely of calcium carbonate derived from the accumulation of shells from marine life.

- *Barrier beaches, barrier islands.* Long sand islands (located just off the mainland) that are parallel to shorelines are called *barrier beaches* or barrier islands. Barrier beaches and islands are visible above high tide and are found only where the ocean bottom dips gently away from the land. For example, they are found off the coastal plains of the southeastern Atlantic and Gulf of Mexico coasts of the United States.

- *Calm water sediments.* Silt and clay are very fine sediments that often are deposited in the quiet marine waters behind offshore bars, in bays or in the deep ocean. Coarser sediments may be deposited in deep ocean basins from submarine debris slides. Neither the fine sediments nor the debris slide sediments are of economic importance as aggregates.

- *Deltas.* Deltas are formed at the mouths of streams where they empty into lakes or oceans. In the case of sluggish rivers, the sediments in deltas are mostly sand, silt and clay, and are not economical as sources of sand and gravel. However, where rivers are vigorous (such as where they come out of mountains) gravel may be deposited in deltas.

Lacustrine Beach: *Lacustrine* (lake) deposits consist of deltas at the mouths of streams, beaches along the shorelines and very soft silt and clay (mud) deposits in the offshore parts of the lake. Sand and gravel in lacustrine delta deposits tend to be stratified and can contain a wide range of particle sizes. In glacial areas, a lacustrine deposit tends to yield better sand and gravel because of the glaciation of unweathered material. Beaches, however, tend to have a narrow range of particle sizes usually consisting of sand and/or gravel. Offshore mud generally is devoid of gravel-size particles except for occasional particles carried in by ice.

Fluvial (Stream) Deposits: Clay, silt, sand and gravel are deposited in river channels or on valley flood plains adjacent to rivers. The particle size deposited depends upon the velocity of the river; a larger stream velocity results in the deposition of larger particle sizes than for a smaller velocity.

- *Channel deposits.* In meandering streams, channel deposits tend to be relatively fine grained up to sand size. Where streams are more vigorous, the channels may contain economically important deposits of sand and gravel. Channel deposits are dredged for their sand and gravel in many rivers in the United States including, for example, the Ohio, Upper Mississippi and the Monongahela rivers.

- *Stream terraces.* When existing fluvial deposits are uplifted as a part of a general elevating of a land mass, the velocity of a stream is increased because of the steeper gradient. The resulting higher energy water cuts through the previously deposited sediments, leaving terraces alongside the stream valleys. Such terraces may contain economic deposits of sand and gravel or may consist of fine flood plain sediments.

- *Alluvial fans.* In arid areas, water moving intermittently with high energy down valleys suddenly undergoes a significant decrease in velocity as it spreads out on the valley floor where it loses energy and deposits its suspended sediments. These alluvial fan deposits are generally fan-shaped and spread outward from the stream canyons where they enter wide valleys. The materials found in an alluvial fan vary from sand to boulder size.

- *Fall line sand and gravel.* The fall line is the trace of the boundary where hilly piedmont topography changes to flat coastal plain topography. At this juncture, the resultant abrupt change in the velocity of a stream causes deposition of coarser sand and gravel. Some of the largest sand and gravel deposits in southeastern states such as South Carolina, Georgia and Alabama occur immediately below the fall line.

Eolian (Windblown) Deposits: *Loess* is dust deposited by the wind. Loess consists of silt-size particles typically 0.02 to 0.05 mm in diameter. The major loess deposits of the world were formed immediately after the draining of large lakes that remained after continental glaciation. Loess tends to be less than 100 feet thick, although loess can be twice as thick in some areas. While loess has no value as aggregates, it frequently covers aggregates resources and needs to be removed.

- *Sand dunes.* Sand dunes are shifting deposits of windblown sand particles. Such deposits are deficient in both silt and gravel-size particles. They are of limited value as aggregates. However, dune sands can be important sources of industrial sand.

Stone Deposits

Sedimentary Rocks: *Sedimentary rocks* are formed either at the earth's surface or under water because of consolidation of sedimentary materials formed from clastic processes. *Clastic processes* are those processes that cause the physical reduction of rock particle size by a combination of weathering and abrasion by wind, water, ice or gravity. Sedimentary rocks also form as a result of consolidation of chemical precipitates such as some marine carbonate mud, spring deposits, and organochemical accumulations such as coral reefs and microscopic siliceous sea shells (such as radiolaria and diatoms).

- *Clastic rocks.* Clastic sedimentary materials harden or indurate over a long period by cementation. Cementation usually is caused by the deposition of silica or carbonate minerals carried by ground water and by compression due to the weight of thick overlying deposits. The most common clastic sedimentary rocks are shale (formed from clay), siltstones (formed from silt), sandstone (formed from sand) and conglomerate (formed from gravel). The most extensive clastic sedimentary deposits were originally marine shoreline and offshore deposits, fluvial deposits (often deltaic) or eolian. Clastic sedimentary rocks are layered (or stratified) with the layers varying from shale through sandstone and conglomerate rock. Clastic sedimentary rock can cover millions of square miles of contiguous land.

- *Carbonate rocks.* Limestones and dolomites usually form as a result of consolidation and cementation of the shells of marine animals or plants. They also may result from the consolidation of fine carbonate mud that is largely precipitated from marine waters. The consolidation of loose carbonate material to hard rock is a complex process of compression, solution and chemical precipitation. The chemical alteration of materials frequently involves the addition of magnesium to limestones resulting in the formation of dolomite.

Siliceous (silica-rich) materials such as detrital pebbles, sand, silt and clay often are found within carbonate rock. Clastic sedimentary rock can be interlayered with carbonate rock. In addition, silica-rich marine waters can chemically precipitate silica as chert usually in nodules or, less commonly, as layers. In such a silica-rich condition, some calcium carbonate shells can be replaced by silica.

- *Miscellaneous sedimentary rock.* Some sedimentary rocks that formed under special chemical or other conditions include iron formations, diatomite or diatomaceous chert (consisting of microscopic, siliceous shells of diatoms) and gypsum deposits. These rocks are usually of little value for aggregates.

Igneous Rocks: *Igneous* rocks form from a viscous liquid silicate melt called magma. In the formation of *extrusive igneous* rocks, the melt is erupted onto the earth's surface as ash, lava flows or very viscous solid chunks. *Intrusive igneous* rocks are those that never reach the earth's surface. Intrusive and extrusive igneous rocks have a similar range of chemical composition but intrusive rocks are coarser grained than the rapidly chilled extrusive rocks.

- *Classification.* Igneous rocks are classified as to origin (primarily as extrusive and intrusive rock), texture and mineralogy. Generally the extrusive igneous rocks are fine-grained (even glassy) because they cooled rapidly from a very hot silicate liquid when they hit the atmosphere. Because of the insulating character of rock, intrusive rocks cool much more slowly than extrusive igneous rocks and as a result, the crystals grow to larger sizes.

  Figure 3.4 gives a simplified classification of the common igneous rocks. As a rule, high quality aggregates can be produced from a wide range of igneous rocks containing numerous different minerals in varying proportions. Hence, details of mineralogy and classification usually are not relevant to producers. In practice, a commercial rock called *granite* may include such rocks as syenite, diorite or even their metamorphic equivalents called granite gneiss, syenite gneiss, or diorite gneiss. Note that gneiss is pronounced as *"nice."* Geologists often use the more precise descriptions in reports and on geologic maps. Hence, these terms are of practical importance to producers.

- *Intrusive rock forms.* Magmas may be forced into other rock (intruded) as crosscutting (discordant) tabular masses called dikes or as tabular masses called sills, which are parallel (concordant) to the layers of sedimentary rock as illustrated in Figure 3.5. The tabular intrusives vary from a few inches to over 300 feet in thickness. The largest intruded igneous masses are irregular, multiple crosscutting intrusions called batholiths and can occur over thousands of square miles. Large intrusive igneous masses tend to be coarse-grained and silica-rich (typically 60 percent to 75 percent silica). The smaller crosscutting intrusives vary from white, silica-rich rock to black, silica-poor rock. Some dark-colored sills are several hundred feet thick and underlie many square miles of surface. Generally, these rocks have around 50 percent silica. These dark-colored sills are called diabase (compositionally gabbro or basalt) by geologists and trap rock by stone producers.

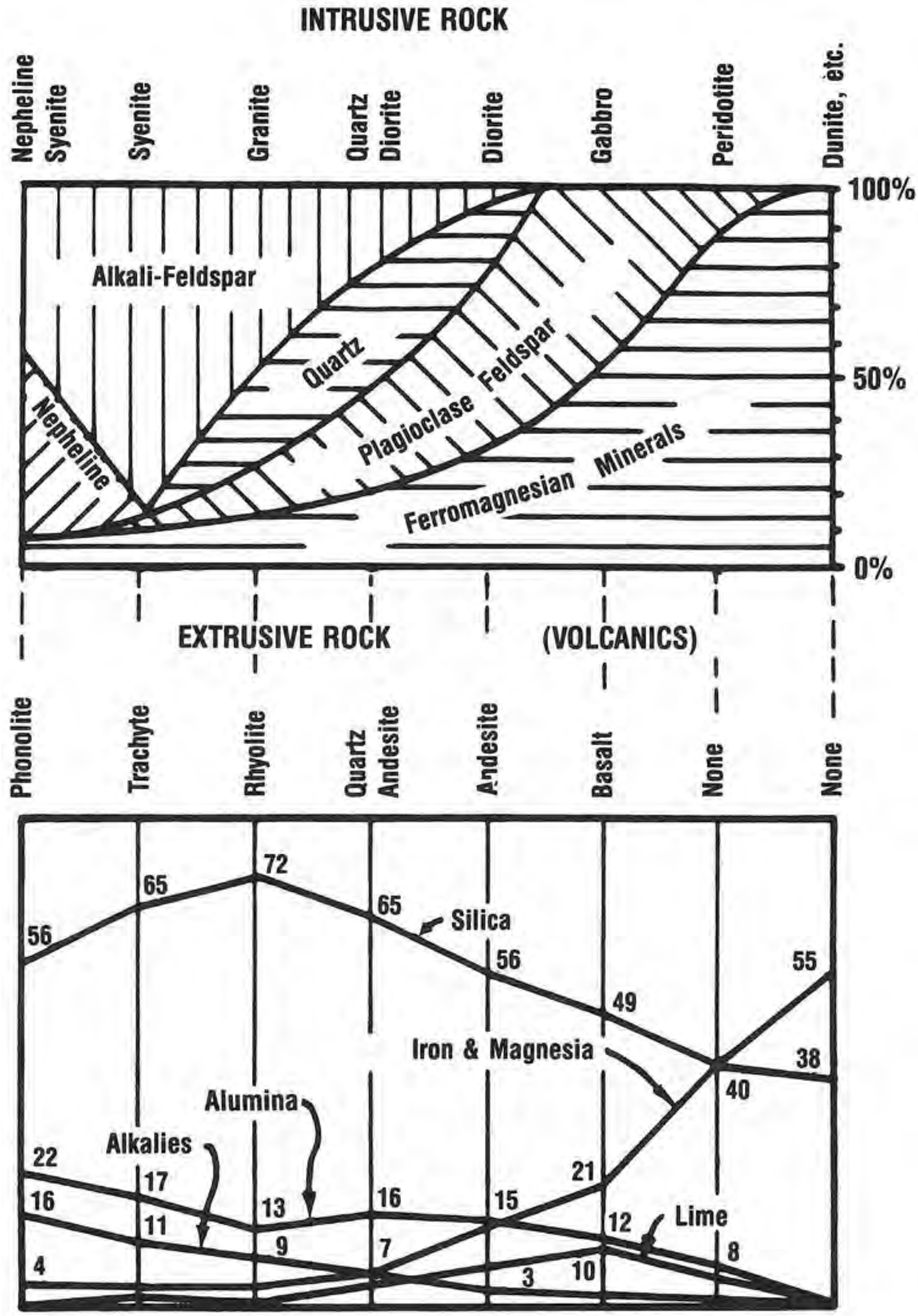


Figure 3.4 Tabulation of Common Intrusive and Extrusive Igneous Rock and their Mineralogical and Chemical Compositions (modified from reference 4)

- *Extrusive rock forms.* Magmas can rise to the surface and form volcanoes. Volcanoes often violently erupt ash, blocks of rock or cinders forming ash or cinder cones. Some ash is erupted as incandescent flows and can devastatingly cover vast areas. Much of the volcanic activity in the Western United States has been of this violent type. Examples of volcanic activity are the Mt. St. Helens' eruption in the state of Washington, and the incandescent ash flow that destroyed the town of St. Pierre on the island of Martinique in the Caribbean in 1929. The violent volcanoes that erupt ash and cinders or blocks often slowly extrude very viscous, glassy rock called *obsidian*. The rock that forms from violent volcanic activity tends to be rich in silica (over 60 percent) and has texture varying from fine grained to glassy. Aggregates manufactured from this rock tend to react deleteriously with the alkali in portland cement.

  Extrusive rock called *flood basalt*, at the other extreme, is erupted relatively quietly from major rifts in the earth's crust. Flood basalts can flow rapidly and form broad plateaus. These basalts are usually dark colored and have a silica content of about 50 percent. The Columbia River plateau of eastern Washington and some of the *trap rock* of the Eastern United States are extrusive flood basalts. Such rock tends to be free of glass, although the crystals may be microscopic.

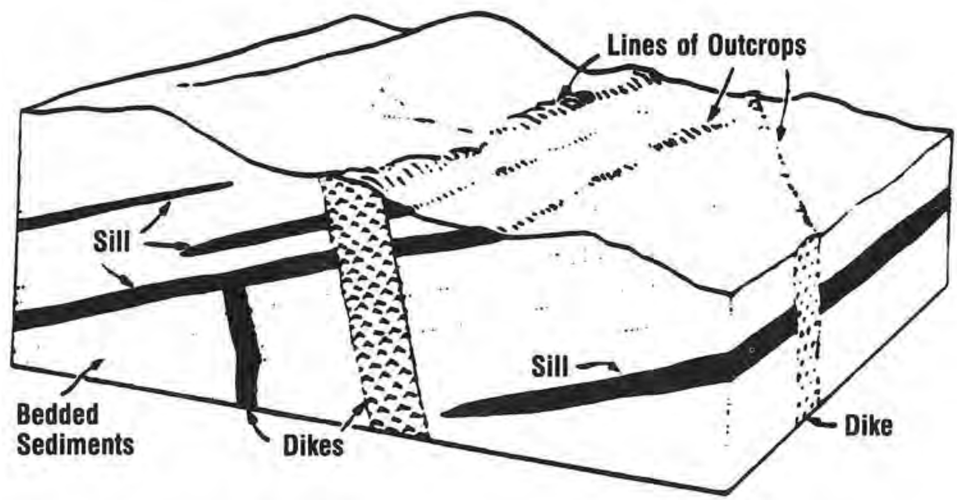


Figure 3.5 Sills are Concordant and Dikes are Discordant Tabular Intrusions [5]

Metamorphic Rock: A sedimentary or igneous rock, when subjected to sufficiently high pressures and temperatures, is altered by re-crystallization to a *metamorphic* rock. Often shear occurs during metamorphism giving the metamorphic minerals a parallel orientation and platey appearance called schistosity. Table 3.1 summarizes some common metamorphic rocks derived from igneous and sedimentary rock equivalents.

Table 3.1 Common Rock Equivalents (Modified from Reference 6)

<table>
<tr><th>Sediments</th><th>Sedimentary Rock Equivalents</th><th>Metamorphic Rock Equivalents</th></tr>
<tr><td>Gravel</td><td>Conglomerate</td><td>Gneiss and Various Schists</td></tr>
<tr><td>Sand</td><td>Sandstone</td><td>Quartzite and Quartz Schist
If from Pure Quartz sand; Mica Schist
If Certain Impurities are Present</td></tr>
<tr><td>Clay</td><td>Shale</td><td>Slate and Schists, Especially Mica Schist</td></tr>
<tr><td>Lime Deposits
Such as Chalk or shells</td><td>Limestone</td><td>Marble</td></tr>
<tr><th colspan="2">Igneous Rock</th><th>Metaphoric Rock Equivalents</th></tr>
<tr><td colspan="2">Granite, Syenite and other Rock with much Felspar</td><td>Gnesiss</td></tr>
<tr><td colspan="2">Fine Grained Felspar Rock Such as felsite and tuffs</td><td>Slate and Schists</td></tr>
<tr><td colspan="2">Diorite, Basalt and other Basic Rock</td><td>Hornblende Schist and Schist</td></tr>
</table>

- *Regionally metamorphosed rock.* Any form of metamorphism that occurs over a large area is called *regional metamorphism*. Regional metamorphic rock can cover thousands of square miles. A good example of a metamorphic belt is one that starts in Newfoundland and extends all the way down the Appalachian Mountains ending in northern Alabama and Georgia. Generally, regional metamorphism is the result of shear stress accompanied by heat. The silica-rich rocks that result from such metamorphism are slates (formed at low temperature) and schists or gneisses which are re-crystallized at higher temperatures. The sedimentary carbonate rock (limestone and dolomite) re-crystallizes under regional metamorphic conditions to form marble, which usually is coarser than its unmetamorphosed equivalents. Silica and other impurities in the sedimentary carbonate rocks usually combine with some of the calcium and magnesium carbonate to form metamorphic calcium and magnesium silicates. Aggregates producers may refer to *marble* as limestone or dolomite. Table 3.1 summarizes the most common sources of metamorphic rock.

- *Thermally metamorphosed rock.* Rocks encountered in the vicinity of large intrusive magmas or other major sources of heat often are re-crystallized primarily by heat. These rocks are called *baked* rock and often are very hard and durable. A slate, for instance, may grade into a very hard dense rock (hornfels) where it is close to a granite. Some marble forms by thermal metamorphism of carbonate rock. In most cases, the original mineralogy is reconstituted to various degrees and new minerals are formed that are in equilibrium with the high temperatures. A sandy dolomite, thus, may alter to a diopsidic dolomitic marble or to a tremolitic dolomitic marble depending upon the temperatures to which the rock is subjected.

3.3 New Trends

Computers

A number of new trends affect geologic and exploration aspects of the aggregates industry. Perhaps the most pervasive is the use of computers in the exploration and evaluation of aggregates sources. Standard engineering software can be employed. Some that are commonly used include *AutoCad* and *Softdesk* from Autodesk, Inc. Microstation from Bently Systems, Inc. and Inroads from Integraph Corp. AutoCad is one of the most popular tools for two- and three-dimensional design and drafting. *Softdisk* is popular with professionals for architectural, engineering and construction projects. *Inroads* is a 2-D/3-D vector based software design system for digital terrain modeling and runs within the Microstation software environment. Other specialized software to assist with mine planning is described in the following section and Chapter 7. Many sources of geologic information ranging from bibliographies to environmental regulations can be accessed directly from the world wide web.

Angular Fine Aggregates

Increasingly, specifying agencies are requiring the use of highly angular fine aggregates in the manufacture of asphalt concrete. Angular aggregates most often are produced using manufactured sand from the crushing of quarried rock. In some instances, sand and gravel deposits with a high percentage of coarse gravel (typically +3 inches in size) can be crushed to meet the requirements for an angular, fine aggregates. The production of large quantities of manufactured sand sometimes leads to the use of rock types that otherwise would be too friable for most coarse aggregates uses. Frequently, certain types of granitic rocks, fractured dolomite and sandstone are used as angular, fine aggregates.

3.4 Variations in Aggregates Quality

Few aggregates resources are homogeneous in their physical characteristics. This section summarizes some of the ways in which aggregates resources can vary between different deposits and within a deposit.

Variations Related to Stone Type

Igneous Rock Variations: Textural considerations. Igneous rocks vary in texture from porous, ashy rock to dense, fine-grained rock. Exceedingly coarse-grained rocks called *pegmatites* occur and have single crystals that are as large as several feet in length. The hardness and resistance of igneous rock to abrasion are usually the greatest when they consist of crystals that are less than about 2 mm in size. Many of the high quality trap rocks are of this type as well as some lava flow rocks of the western United States and granites of the Appalachians.

- *Compositional factors.* The high-silica volcanic rocks often are glassy even though the glass may not be visible without magnification. The very viscous lavas and consolidated incandescent ash flows that are found in some parts of the western United States are frequently glassy. Such glasses often are highly reactive chemically with alkali in portland cement and hence are unsatisfactory in exposed portland cement concrete.

- *Texture.* Igneous rocks owe much of their strength to the tendency for the grains to interlock and thus resist abrasion. The interlocking grains in trap rock are responsible for its usual high quality. However, *olivine* [(Mg,Fe)2SiO4)], which frequently occurs in trap rock, tends to occur in somewhat rounded grains causing the nearly pure olivine rock (dunite) to be friable and some olivine-rich trap rock to be weak. Micas do not usually interlock with other minerals and when concentrated create zones of weakness. Quartz, on the other hand, usually tightly interlocks with other minerals and is a major source of strength for many rocks.

- *Differentiation*. During the crystallization of low viscosity, silicapoor igneous melts, minerals may be segregated in layers by a process called *magmatic differentiation*. Since trap rocks often are segregated in this way, they vary in quality largely because of the weakening effect of the mineral olivine that often concentrates near the base of trap rock masses.

Metamorphic Rock Variations: Slates. Metamorphic rocks that have re-crystallized because of shear at relatively low temperatures include slates. *Slates* tend to be platey and generally are unsatisfactory for use as aggregates because they crush to flat particles or may be unsound.

- *Schists and Gneisses. Schists* are formed at higher temperatures under regional shearing and re-crystallization conditions. Schists usually are sounder than slates but still may form flat particles upon crushing. Thus, schists are often of marginal quality. However, if the chemistry of a rock is such that the platey micas or elongated amphiboles are not present, flat particles may not form upon crushing. For example, rocks such as quartzite (metamorphic sandstone) or marble (metamorphic carbonate rock) often make excellent aggregates even though they may occur in an area with schists, which are not acceptable.

- *Gneiss* is a sheared, re-crystallized metamorphic rock that usually is defined by geologists as having less than 50 percent mica but is otherwise similar to schist. However, a rock with more than 10 percent to 25 percent mica is likely to be of unsuitable quality for many uses because of unsoundness and because of the occurrence upon crushing of an excessive amount of flat particles. Thus, some gneisses cannot be readily processed to give a high quality aggregates. When the surface of adjacent plates of mica in a gneiss rock is more than about 20 mm apart or the mica content is less than about 10 percent, excellent aggregates usually can be produced.

- *Localized Schistosity (Shearing).* Deep in the earth's crust, rocks may be at a temperature at which a new mineral assemblage can form and be stable. In the absence of regional shearing, however, the new mineral assemblage may not form. When such rocks are sheared locally, zones of new stable minerals in the form of a *platey schist* as narrow as about three feet may traverse otherwise high-quality rock. At lower temperatures, shearing along fault zones usually greatly weakens a rock and re-crystallization may not occur.

- *Hydrothermal Metamorphism*. Many rocks are altered by hot water *(hydrothermal metamorphism)* with the resulting altered rock usually being unsatisfactory as an aggregates. Lava flows, granite and trap rock can have isolated zones of hydrothermal alteration causing these zones to be porous or clay-rich and hence unsatisfactory as aggregates.

- *Amphiboles.* Metamorphic processes may cause various amphiboles such as *actinolite, tremolite* and *anthophyllite* to form. These amphiboles usually occur as brittle crystals, but rarely occur locally as fibrous varieties called *asbestos*. The mining, processing and use of asbestos are closely regulated by government agencies and are not part of the aggregates production industry. Amphiboles can be found in any marble or other rock in which carbonate minerals were original constituents. Such minerals also commonly form by metamorphism of the silica-poor igneous rocks such as trap rock or serpentine.

Sedimentary Variations: Clay-rich rock. The major clay-rich rock is shale. Shales are usually unsatisfactory for aggregates because of their tendency to form flats on crushing and because they disintegrate (slake) upon wetting and drying. Shales occur as continuous layers over wide areas, as lenses a few feet wide and a foot or so thick, and as paper-thin layers (partings). Shale lenses often fill ancient channels in sandstone and hence frequently wander erratically through a sandstone deposit. Any rock (such as limestone or sandstone) that contains shale in layers may be unsound as aggregates because of the slaking along the shaley layers. Shaley rocks also tend to deteriorate when subjected to sulfate soundness and freeze/thaw tests.

In some instances, carbonate rocks containing minor amounts of clay develop dolomite crystals upon the addition of MgO. The dolomite crystals usually are clear because impurities such as clay are forced to the edge of the crystals. A network of such noncarbonate impurities around dolomite crystals can cause a carbonate rock to be unsound because of a tendency to deteriorate upon wetting and drying similar to the way a shale slakes.7 Dolomitic limestone of this type may falsely appear to be sound in fresh cores with shale partings being absent or rare.

- *Cementation.* Sedimentary rocks vary in abrasion resistance and may be friable (i.e., poorly cemented) to compact and dense (i.e., well cemented). Cementation may be irregular. For example, sandstones often are cemented with silica where they outcrop but are poorly cemented and friable behind the outcrop.

Some limestones, such as reef rock and shell conglomerates known as coquinas, are poorly cemented when first formed but on compaction become cemented and hard. The age of sedimentary rock frequently influences their quality. Old sedimentary rocks, which are common in the Eastern United States, tend to be better cemented and of better quality for aggregates use than the younger but otherwise similar rock found on the West Coast.

Quality Relative to the Origin of Sand and Gravel

Influence of Bedrock in Glaciated Areas: The quality of sand and gravel is heavily influenced by the nature of the bedrock from which the sediments were derived. Sand and gravel derived from sound rocks, such as many igneous and metamorphic rocks, tend to be sound. Sand and gravel derived from rocks rich in shale, siltstone or other unsound materials tend to be unsound. In areas where the bedrock is of marginal quality, kame deposits occurring at the edges of valleys tend to be of poorer quality and lower soundness than kames or outwash deposits in the middle of the valleys because the edges of the valleys receive the greatest contribution from the unsound local rocks.

Sand and gravel deposited at high elevations from water associated with ice (i.e., from kames, eskers, etc.) may be superior to similar deposits in lowland where the bedrock is of poor quality. The reason is that rock high in an ice sheet has been carried from higher, more mountainous areas, which tend to consist of hard, sound rocks.

Influence of Types of Deposition: Sand and gravel that have been subjected to prolonged agitation by water usually are of better quality than less abraded sand and gravel. Thus beach sands, because of wave action over extended periods, tend to have low soundness losses although the gradation tends to be uniform. Glacial outwash channel deposits often are of better quality than kame and esker gravel in the same area because the outwash channel sediments have undergone more wear. The coarse debris in drumlins is frequently of poor quality; however, the quality is rarely tested because drumlins are usually not economic aggregates sources due to gradation problems.

Weathering Effects

Chemical Weathering of Rocks: Prolonged weathering under warm, humid conditions profoundly alters most igneous, metamorphic and sedimentary rocks. In the Southeastern United States, such weathering causes saprolites to form in which there is often a gradation from a clay-rich or hydrous iron-aluminum oxide-rich soil, through the friable material called *saprolite* (which often mimics the structure of the original rock) to the original bedrock. In some parts of the world, the weathered zone is over 300 feet thick, the depth of weathering being a function of climate, local elevation, slope, water table depth, nature of the bedrock, and time. The quality of the materials for aggregates generally is gradational with an upper zone that usually must be stripped, an intermediate zone of sandy silt and silty sand that generally is suitable as fill, to a fresh rock that may be suitable for high-quality aggregates.

Influence of Salt and Colloids: Chemical weathering always releases salts and colloids that are carried away by percolating water. The salt may be dissipated or concentrated and has a profound influence on the quality of some rock.

Case hardening can occur in arid areas where pebbles tend to develop a hard shell. Case hardening occurs because of the deposition of salts or colloids (usually calcium carbonate or silica) that were dissolved from the inside, carried outward and re-precipitated at the outer edge of the pebble. Thus, pebbles in desert areas may seem quite hard, but inside they actually may be weak or friable.

Case hardening also occurs in non-arid areas, such as the eastern United States. Evaporation of water from an outcrop surface causes cementation of grains on the surface. Thus, dense, sedimentary quartzites may be found at an outcrop. Such outcrops may not be representative of a sandstone or conglomerate a few feet behind the outcrop where the rock might be poorly cemented and friable.

Sand and gravel deposits are commonly cemented by calcite at the water table. Cementation occurs because calcium carbonate leaches from the sand and gravel above the water table and is carried downward to precipitate as a cement. The zone of cemented sand and gravel becomes a type of conglomerate rock (which is often called "caliche" in the western United States). The leached sand and gravel above the water table usually is of poorer quality than the unleached sand and gravel below the caliche zone.

Soluble salts such as sulfate and chloride also are released by weathering. The crystallization of salt in rock pores often causes rock to deteriorate at their outcrops. This natural process is similar to that occurring in a sulfate soundness test and also is responsible for much deterioration at the base of masonry walls and monuments. Although the process is most obvious in arid areas, it also is observed in humid regions. For example, sulfate salt in aggregates from an area in Virginia (where alum springs occur) caused deterioration of aggregates in the base course under an asphalt pavement.[8] A similar situation was observed in South Africa,[9] where the sulfate was released because of weathering of sulfides, which was interpreted as occurring in pavement bases after being constructed.

Physical Weathering: Changes in temperature, humidity, freezing and thawing, and wetting and drying are several cyclic physical changes that cause stress within rocks. Outcropping rocks may greatly be influenced by these environmental effects and often lose strength as a result.

- *Wetting and Drying, Humidity Changes.* When subjected to alternate cycles of wetting and drying or humidity changes, some rocks deteriorate by a process called slaking. The most common example is shale, which rarely outcrops because it deteriorates so fast on exposure to the environment. Other rocks that contain layers or partings of shale also tend to deteriorate along these layers. Some dolomitic carbonate rocks, as discussed in Section 3.3, and some weathered or hydrothermally altered rocks may contain clay in a disseminated form. Often such rocks are unsound on wetting and drying or disaggregate rapidly when subjected to abrasion, sulfate soundness or freeze-thaw tests.

- *Freezing and Thawing.* Water expands 9 percent when it changes to ice and if there is no space available to accommodate the expansion, enormous forces are created. Thus, cycles of freezing and thawing of water-saturated rock may cause deterioration. It is not always clear whether a rock deteriorates by slaking or freezing and thawing. Some water-saturated rocks are perfectly stable when subjected to freezing and thawing in outcrops. Stability occurs because the water, which is driven ahead of expanding ice, migrates into the rock and hence does not build up enough hydrostatic pressure and expansive force to cause sufficient stress to break the rock. However, the same rock removed from a quarry face and allowed to freeze evenly on all sides before it has lost its normal rock water (sometimes called quarry sap) may break. This type of failure has been observed in graywacke building stone and in some dolomites in New York that were quarried and immediately frozen before sufficient drying had occurred. Under these conditions, the rock may break during freezing with a sudden, sharp snap.

- *Temperature Cycling.* Some rocks suffer considerable internal strain from temperature cycling, such as coarse-grained dolomitic or calcitic marble, which have a strong preferred crystal orientation. The reason is that the carbonate minerals have great differences in thermal expansion in the two major crystallographic directions. In addition, some rocks that contain hydrated minerals dehydrate in the sun and then rehydrate on cooling. This phenomenon is part of the slaking process described previously.

Influence of Climate on Sand and Gravel Quality: Granular sediments derived from areas of prolonged, deep weathering under humid conditions tend to be of high quality. This, for example, is true in the Southeastern United States, where the rocks have been weathered for tens to hundreds of millions of years. Only the hard, durable minerals such as quartz survive and concentrate in the sand and gravel accumulations. The opposite situation is found in major glaciated areas where continental ice sheets have stripped soil and weathered rock cover. The sand and gravel in these areas tend to be of lower quality than in areas of deep chemical weathering.

In arid regions, weathering effects also may be locally deep but for the common silicate minerals, the effects are usually not deleterious. However, sulfides may be completely deteriorated to depths of a thousand or more feet, appreciably weakening sulfide-rich rock.

Influence of Sedimentary Recycling: Many recent sands and gravels have been derived from older sand and gravel deposits. As a result, some sand and gravel particles have been recycled one or more times over millions of years. These old particles are the hardest and have the best quality because only durable particles can survive prolonged attrition and associated chemical weathering. Much of the well-rounded beach sand of the Southeastern United States has been through several cycles of erosion and deposition.

3.5 Mine Related Computer Software

The value in geology and exploration of using available software that runs on a personal computer is to easily store, manipulate and report the large quantities of data involved. Computer aided mine planning utilizing exploration data allows for rapid changes of mine reserve analysis due to changes in assumptions of land use, marketing, product quality, product mix and permitting. A wide variety of computer software programs can be used to process subsurface information including the creation of topographic surfaces and maps showing the thickness of formations, overburden or other geological units. With the addition of quarry-face setbacks, quarry face configurations and rock loss factors, these programs can quickly and accurately calculate rock reserves. Specialized personal computer based software packages such as *PC-Mines*S4 and *TECHbase*,[5] will model aggregates deposits, rock quality and economic factors, help develop mine designs including ramp and haul roads. They will plot results in graphic forms suitable for storage and manipulation of material quality and boring information. Using initial assumptions about the deposit, these mine planning software systems can assist in comparing different possible mining sites and making rational decisions about further mine exploration and development. Mine design and reclamation software can make visually attractive plans that are useful in seeking government approvals.

3.6 Exploration and Evaluation

Introduction

Problem Definition: In most cases, the job of the exploration geologist is to locate a viable aggregates deposit to supply a given market at a competitive price. The price charged for aggregates includes the cost of development of the aggregates mining facility, which is usually amortized over a long period. The price charged for aggregates also includes hauling, processing, regulatory expenses, sales and administration costs along with a reasonable profit. These costs must be estimated and considered very early in evaluating the economics of a new aggregates source. Exploration is thus much more than simply finding a source of suitable material and includes the overall evaluation of the economics associated with quarry development.

This section briefly considers regulations and haul costs, which are discussed in more detail in Chapters 4, 6 and 10. Techniques are considered to optimally locate and define the quality, quantity and configuration of aggregates deposits. Finally, the nature of aggregates reserves (i.e., the minimum available aggregates resource expressed in volume or tons) is discussed in some detail.

The Geologist's Task: Usually only a single, new deposit is most suitable for a given market. The task of the geologist is to locate this deposit.

Principle of the Weakest Point: During all phases of exploration a weakest point exists that must be analyzed, at least to some extent, before other aspects of exploration can proceed. The weakest point usually shifts because as one point is understood and compensated for, another weakest point replaces it. Examples of the weakest point concept are:

1. To explore an area extensively when a zoning restriction makes it impossible to open a new operation is obviously a waste of money. Therefore, exploration should proceed only after the zoning situation, which is the weakest point, is better defined and understood.
2. Conversely, to go to the expense of obtaining total assurance that all zoning or political obstacles are removed before the quality of the aggregates materials has been determined at least preliminarily also may be money badly spent.
3. To explore a piece of property extensively without obtaining at least an option to purchase the land is another case of not addressing a weak point in proper sequence.

Thus, exploration always requires enough judgment and experience to enable the geologist to conduct his work in a logical sequence. Excessive funds should not be spent to solve one problem to a 100 percent level of certainty, when another major problem has yet to be addressed. In other words, each weak point should be addressed and solved to an acceptable probability, and then the next weak point addressed, and so on. Frequently, at a later stage of exploration, early weak points should be readdressed and then resolved to a new lower level of risk.[10]

Political, Regulatory and Social Factors

Localized Regulations: The development of a source for potential aggregates production usually is significantly influenced by zoning regulations at the town or county levels and even at the state level. Regulations usually encourage community participation in hearings. Hearings are held before political or bureaucratic bodies, such as town boards or hearing officers. The views toward aggregates producers of the local public and their political representatives usually must be carefully analyzed.[11] These aspects are covered in detail in Chapter 4.

Federal Regulations: Federal regulations regarding various minerals that are believed to threaten human health are also a factor in exploration. In addition, regulations pertaining to work safety are of importance in exploration and are discussed in Chapters 4 and 6.

When to Consider Regulations: The implications of relevant ordinances and regulations must be considered very early in exploration because they may effectively eliminate some tracts of land as being viable, potential sites.

Transportation Factors

Importance of Transportation Routes: In virtually all cases, the economic viability of an aggregates deposit is a function of the cost of moving the finished products to the market compared to the cost of moving competitive aggregates to the same market. Exploration starts with an analysis, or at the least an understanding, of haul routes and the costs of moving products to the markets by various truck, water or rail routes. During this early phase, knowing details of haul costs is not usually necessary, but an awareness of their approximate magnitude is important. Thus, the search for a new deposit is usually concentrated near suitable transportation routes that can economically access the marketplace.

Variations in Haul and Handling Costs: Hauling and handling costs of aggregates are highly variable. Trucking costs may be quite low in areas of minimal delays, but the costs are much higher when there are impediments caused by traffic, traffic lights or low speed limits. The costs may vary from $0.10 or less per-ton-mile in rural areas to several times this in metropolitan areas. Somewhat similarly, rail costs vary greatly with the rail lines and with the number of rail lines that are used. Rail costs tend to be about 20 percent to 30 percent of the ton-mile trucking costs. Water transportation costs vary with the size of the vessels and with the number of locks if the aggregates are barged. Usually the costs are 10 percent to 20 percent or less of trucking costs. The cost of loading and unloading facilities and of handling and storage for rail or water transportation is usually more than for truck transportation. However, under some long haul conditions, the cost advantage of moving large quantities of aggregates by rail or water far outweighs any disadvantages.

Final haul costs are generally not determined in early phases of exploration. The exploration geologist, however, always must be sensitive to the influence of hauling costs (which are discussed in Chapter 10) on the viability of a prospective aggregates source.

Site Selection—Sand and Gravel

Land Form Analysis: A sand and gravel deposit usually has a characteristic landform. Working with a standard topographic quadrangle map at a scale of about 2,000 feet to the inch, an experienced geologist can select most locations where sand and gravel may occur. Aerial photos, which are available for most areas, also can be used to advantage in performing this type of initial investigation. Aerial photos are often available through the local geological survey or it will know where aerial photos can be obtained. Aerial photos provide the most detail for landform analysis including stereographic viewing. However, because sand and gravel deposits usually must have significant size to be viable, and the topography of their features is relatively large, the standard 2,000 feet to the inch topographic maps usually are adequate and are less expensive to use than aerial photographs. When the only maps available have a scale of a mile or more to the inch, the maps are of less value to the geologist because some deposits could be missed.

- *Gradation.* Gradation is a critical characteristic of any sand and gravel deposit because aggregates are sold in specific graded sizes. Generally, sand and gravel deposits with coarser particles are superior to deposits of finer-size particles because finer sizes can be made from larger ones, but the reverse is not true.

Table 3.2 gives a summary of the typical materials found in each landform. Before field exploration work, the geologist may have a reasonably good idea of the size, gradation and quality of the various sand and gravel deposits based on his knowledge of their geologic origin.

Table 3.2 Landforms and Gradations

Landform	Gradation *, **
Beach Terrace	Sand (Gravel)
Flood Plain Terrace	Silt and Clay
Channel Terrace	Sand and Gravel (Clay)
Glacial Outwash Channel	Sand and Gravel (Clay)
Delta, Meandering River	Silt and Clay (Sand)
Delta, Vigorous Streams	Sand and Gravel, Close to Mouth, Finer Away From Mouth
Esker	Sand and Gravel (Clay)
Kame	Sand and Gravel (Clay)
Alluvial Fan	Bouldery Gravel and Sand
Drumlins, Lodgement Till	Compacted Silt and Clay with Gravel and Boulders

* *Minor components are in parentheses.*

** *Definitions of sand and of gravel vary. Soil engineers and geologists define gravel as any particle greater than the U.S. Standard No. 4 sieve size (about 1⁄16 in.) and less than three inches. For aggregates producers, fine aggregates are colloquially called sand and fine aggregates and usually include particles below 3⁄8 in. in size. Thus, fine aggregates include sand and some gravel as defined by engineers and geologists.*

Site Selection–Stone

Zeroing In: The first requisite for locating sites underlain by stone suitable for the manufacture of crushed stone products is to understand the distribution of various rock types in the area of interest. Usually maps of the bedrock geology are available from the state geological survey or from the United States Geological Survey. When geology maps are not available, learning the nature of the bedrock requires geologic mapping, air photo interpretation, geophysics or other methods of geologic reconnaissance. Quarries that already are in the area can provide valuable information about rock types that have proven to be satisfactory in the past although suitable rock may not be restricted to those types.

Understanding Outcrops: Once a potential site is located, any rock exposure available at the site should be investigated. The exploration geologist must be acutely aware of why some rocks outcrop and why other rocks do not. Several case histories illustrate how outcrops can be deceptive:

1. *Granite Outcropping*. A glaciated area of low, rounded hills had outcropping granite on every hill suggesting that the whole area was underlain by granite. In actuality, the swales between the hills were all underlain by unsatisfactory marble that had been eroded down by glacial action. Thus, the conclusion that all of the rock was sound granite would have been incorrect. Often the softer, least resistant rock is more easily eroded or dissolved and therefore forms the valleys and other lower areas, as was the case in this example.

2. *Limestone Cliffs.* A 45-foot to 60-foot cliff of horizontally layered, high-quality limestone appeared to be an excellent potential quarry site. However, between the limestone outcrops, areas of non-outcropping, unsound dolomite layers were present. The unsound dolomites were sensitive to alternate wetting and drying.

3. *Sandstone Cliffs.* Graywacke sandstones outcrop prominently in the area of the Catskill Mountains of New York extending south and westward into Pennsylvania. Non-outcropping shales virtually always occur between the sandstone layers. Again, the visible outcropping of sandstone is not typical of the entire deposit.

4. *Case Hardening.* The case hardening effects commonly found in certain porous rocks (such as sandstone) produce outcrops of deceptively good quality. The layers behind the outcrops may be poorly cemented. Case hardening is encountered in the graywacke sandstones of New York and Pennsylvania and many quartz conglomerate rocks of the Appalachian chain and some Western states.

5. *Igneous and Metamorphic Rocks.* Most igneous and metamorphic rocks tend to be of poorer quality at the outcrop than at depth because of weathering of feldspars and other complex silicates. Hence, any tests made on outcropping rock may indicate a lower quality rock that is not representative of the deposit at depth.

6. *Sand and Gravel.* In the North Central and Northeastern United States, the sand and gravel immediately below the topsoil in exploration pits may fail soundness tests because of the leaching out of calcium carbonate cement. The same deposit at depth may be acceptable.

Consider carefully the nature of visible evidence of rock quality and continuity, and be aware that the appearance of an outcropping can be deceiving. In all of the above cases, samples taken from or near the surface were not representative of the underlying deposit.

Geologic Mapping

Rationale for Geologic Mapping: The geology of a property must always be sufficiently known so that all critical variations in rock quality are understood. Mapping the geology is a way of systematizing field observations, and it is valuable for planning drilling and other sampling operations. In cases of complex geology such as the New York City area illustrated in Figure 3.6, mapping is usually essential to comprehend the variations in rock quality. Formal geologic mapping may not be required if the geology is simple. For example, where rocks are horizontally layered or folding is not complex, the only field observations may be determinations of bedding angles and identification of rock types. In any event, detailed geologic mapping should rarely be performed early in exploration. As a practical matter, detailed geologic maps may never be required for some operations.

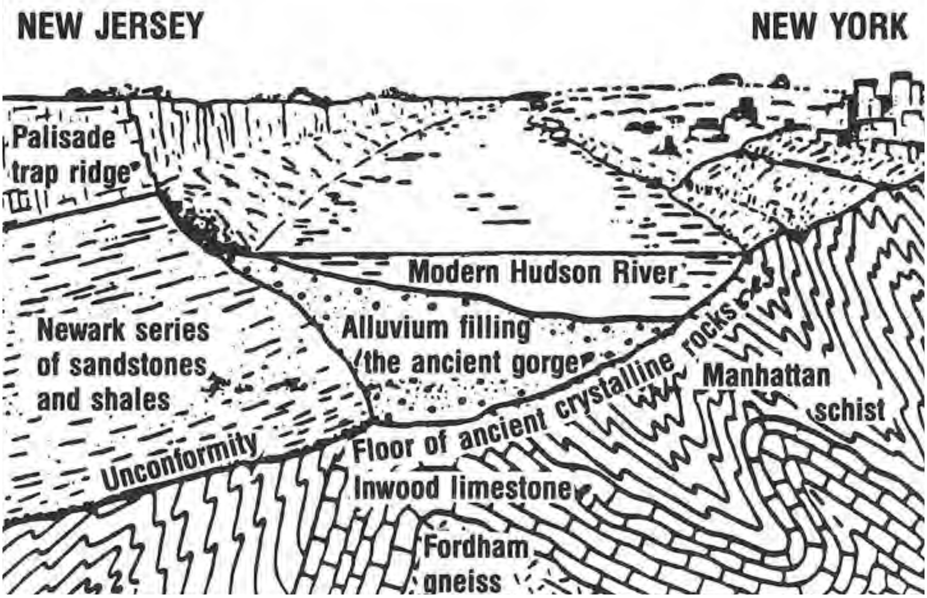


Figure 3.6 Complex Geology of the New York City Area[12].

Base Maps: Base maps of properties can be as simple as property boundary maps. They may be as complex as topographic maps made at a scale of 100- or even 50-ft-to-the-inch from specially flown stereographic aerial photographs. When the geology is complex and quality control difficult (Figure 3.6), or when engineering problems are severe, preparation of a geologic map is prudent. The selected scale and contour interval are primarily a function of the complexity of the topography and the amount of details that need to be included on the map.

The techniques for geologic mapping and interpretation are not discussed here because of their complexity. Any mapping should be performed by geologists familiar with the requirements of the aggregates industry. Detailed discussions of mapping are given elsewhere.[13]

Methods of Obtaining Samples

Introduction: Systematic sampling of the aggregates source is basic to determining reserves. The nature and trend of the layers must be known well enough so that the position of each sample relative to the layers that ultimately will be mined is understood. All pits, drill sites, or other sampling locations should be plotted on maps. Sampling should be sufficient to allow the evaluation of the quality, quantity and configuration of all layers or zones to be mined. When a layer is sampled for testing, the entire layer intersected by drilling, trenching or other methods should be sampled. Enough samples should be taken of each zone so that its critical characteristics are known. In addition, multiple sampling of zones allows for checking on the quality of the test results, i.e., test results for a particular zone should be similar. Duplicate samples routinely should be sent to testing laboratories as a further check on laboratory results. Finally, assurance should be obtained at an early stage that the test results received will be essentially the same results that the specifying governmental agency in whose jurisdiction the producer markets his products will obtain on the same samples. Sampling techniques also are described in Chapter 18.

Types of Samples: The types of samples commonly taken are as follows:

1. *Grab Samples.* Grab samples are preliminary only and rarely can be considered typical of a deposit. Grab samples can be taken from pits, off outcrops, out of cores, from quarry or pit walls, stone product piles, or muck piles. In each case, the person performing the sampling should attempt to obtain typical, representative material. To obtain the best sample from a product pile, the sampler should follow procedures outlined in ASTM D75-8714 because piles tend to segregate. The sampler should realize, however, that even under the best of circumstances, grab samples rarely are representative of the deposit. If properly taken, grab samples may be representative of a muck or product pile.

2. *Shot Samples.* In some cases, rock is shot from an outcrop or from a quarry face for testing purposes. If only some of the rock is sampled, it must be considered a grab sample. It is preferential to take all of the shot material for testing purposes. Still, a sample of shot material, large though it may be, is probably representative of only a limited part of a deposit. The degree to which it is likely to be representative of the whole or of a segment of the deposit should be determined by an experienced geologist.

3. *Pit Samples.* Samples of sand and gravel can be taken from excavated pits. Pit samples are relatively inexpensive to take and several samples can be obtained in a day. Care should be taken to sample around and well into each pile of excavated material. The person performing the sampling should observe and, preferably, log the pit layers to be certain that whatever material is taken reasonably represents the gradations of material to be mined. Any sample obtained from a pit is likely to be leached of cementing carbonate minerals and therefore may not fairly represent the quality of the resource at depth.

4. *Core Drilling.* A typical core drilling set-up is shown in Figure 3.7. If possible, cores should be taken approximately perpendicular to the direction of rock layering. The size of core that is taken is a compromise between cost, recoverability, quantity and ease of handling. Although cores may be as small as ⅝ inch or as large as 36 inches in diameter, the most frequently used sizes are NX (2⅛ inch core diameter) or NQ (2-inch core diameter). The spacing and number of core drill holes are dependent on the complexity of a deposit and on the purpose of the drilling. A typical spacing for core holes is 400-foot centers or one hole per four acres. But when rock is homogeneous over large areas a wider spacing can sometimes be justified. Great geologic complexity may, in other cases, require much closer spacing.

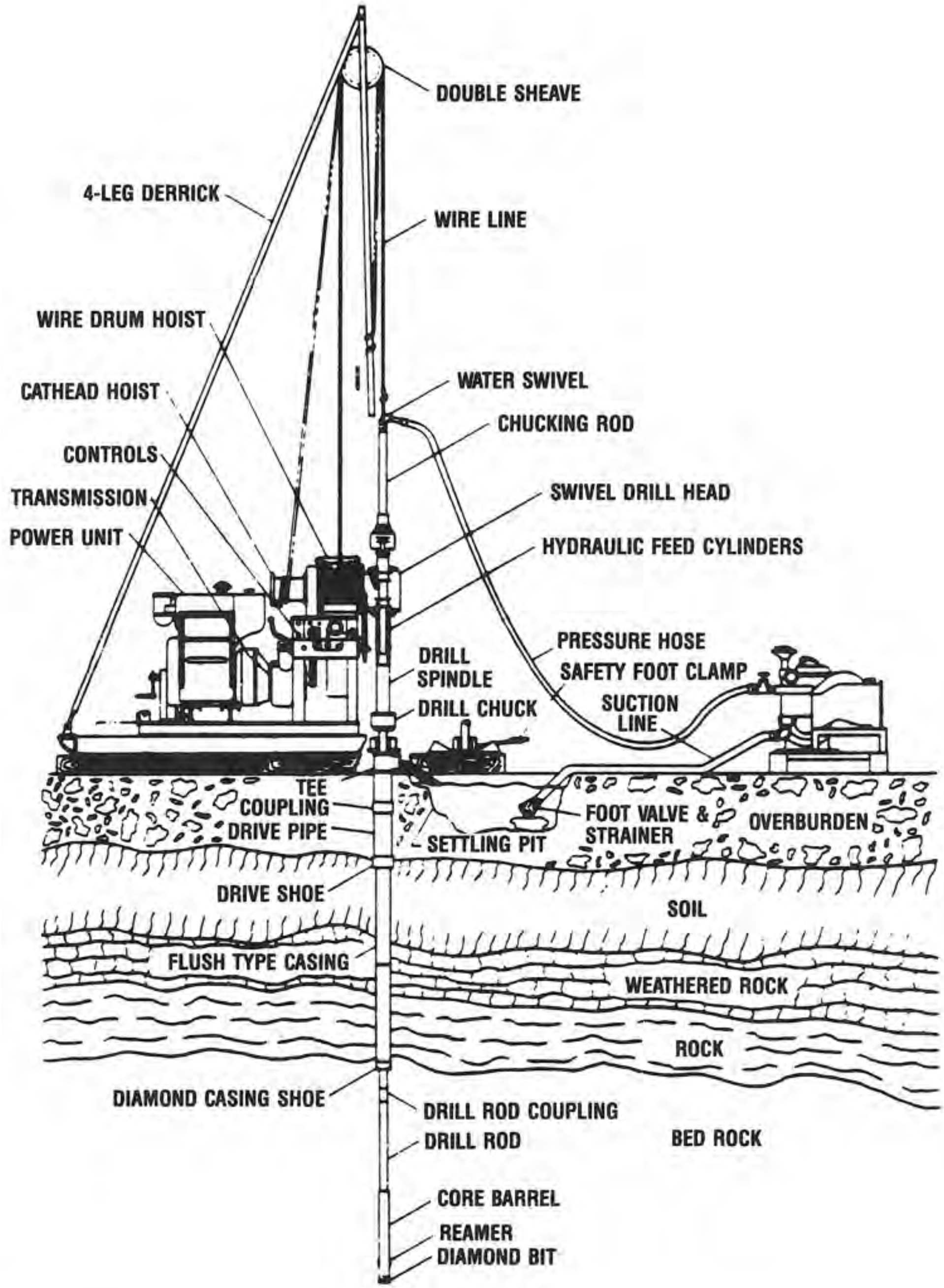


Figure 3.7 Schematic of Typical Diamond Core Drill Rig[15].

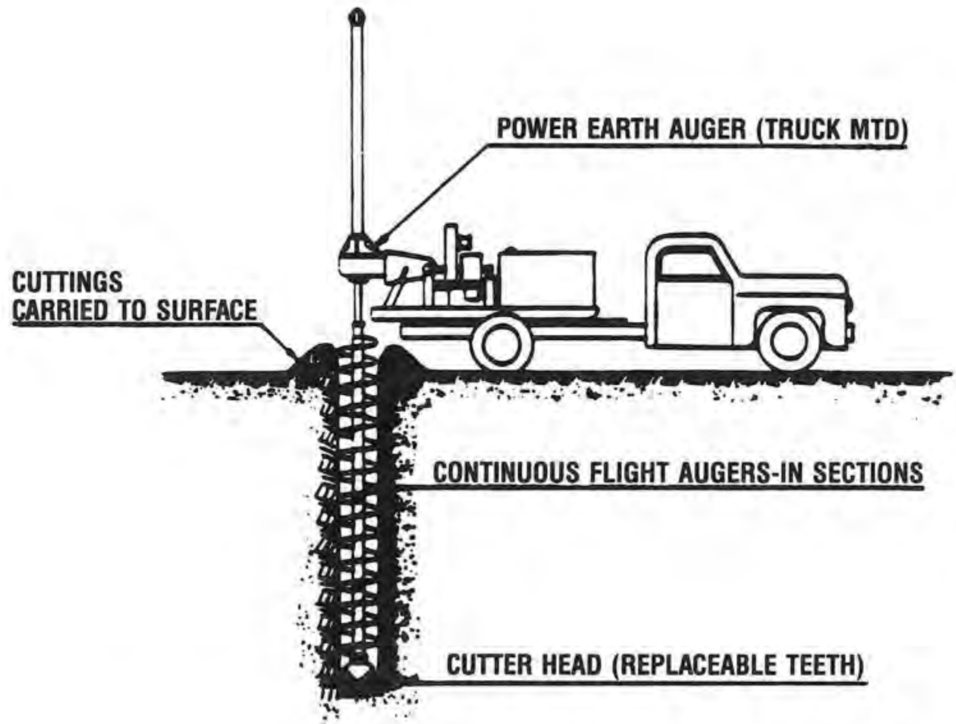


Figure 3.8 Continuous Flight Augers Used for Sampling Sand and Gravel Deposits.[15]

5. *Drilling Sand and Gravel Deposits.* Several methods are used to drill into sand and gravel deposits. A geologist or supervising engineer should be at the drill rig during all drilling no matter what method is selected.

Auger drilling (Figure 3.8) employing a 6-inch diameter or greater auger can be used to obtain samples of sand and gravel deposits. In areas where the quality and gradation of deposits are not particular concerns, but till or clay and silt layers are problems, the auger method works very well. An experienced driller usually can determine by how the drill acts what type of material is being drilled. Samples obtained from auger drilling are mixed and hence the actual layer from which a sample originated is not necessarily known. Logging of auger holes should be performed by a geologist or engineer at the drill rig.

Bucket augering consists of pushing a casing into a hole typically 12 to 24 inches in diameter with bucket samples being taken from below the casing. Bucket augering can be used when large representative samples are essential. This method is probably the best technique for obtaining truly representative samples of sand and gravel deposits, but it usually is not employed because of its high cost.

Some drilling systems force air or water down the stem of a hollow auger, driving the sand and gravel that is penetrated back to the surface where it is collected. This type of drilling is relatively inexpensive, but the samples are mixed and the precise gradation of each layer encountered is uncertain. In the case of a water return, the gradation of a sample may be more related to the velocity of the return water than to the in situ gradation because the water tends to wash out the fines and may not be able to carry the larger particles up the hole.

A hollow tube that is split down its length, called a *split spoon sampler*,[16] can be hammered into a deposit and then pulled out as shown in Figure 3.9. The tube is opened and the loose material within it removed as a sample. Split spoon sampling should be continuous, to obtain the best indication of the nature of a deposit. This type of sampling is usually preferred over other types because it is relatively inexpensive and sampling is continuous. However, the size of particles returned is restricted by the size of the tube. A generally acceptable split spoon sampler size is a 3-inch outside diameter tube. Particles over about 2 inches in size, however, will not enter the barrel and hence the sample is biased toward the smaller-sized particles.

Sand and gravel deposits can be explored to depths up to about 20 feet using backhoe-type excavation equipment. Excavation permits sampling from known depths and includes all material sizes. The shallow depth of backhoe samples limits their value.

Logging Sand and Gravel Samples and Rock Cores: A geological or engineering description of cores or sand and gravel samples taken is required before selection of samples for engineering or other analyses. Descriptions should employ standard terminology, standard symbols and standard colors to minimize the possibility of subjectivity and misunderstanding.[17]

Unsplit rock cores are frequently logged for certain engineering purposes such as for analysis for the design of tunnels, dams and building foundations. Table 3.3 summarizes the parameters that can be used to describe the rock along with its standard symbols. Generally, rock cores with strong decomposition, weak strengths, considerable fracturing, low hardness or low rock quality designation (RQD) tend to make poor aggregates. Determining such parameters is not a substitute for systematic testing, but these observations allow a greater element of predictability for test results.

Core logging of rock types in most cases should be performed on a core that has been split. Core splitting is performed using equipment in which a hammer or hydraulic press drives steel wedges, which splits the cylindrical core longitudinally. Working with a split core has two advantages: (1) a fresh surface is available for observation; and (2) half of the core can be sent for testing while the other half is retained for reference.

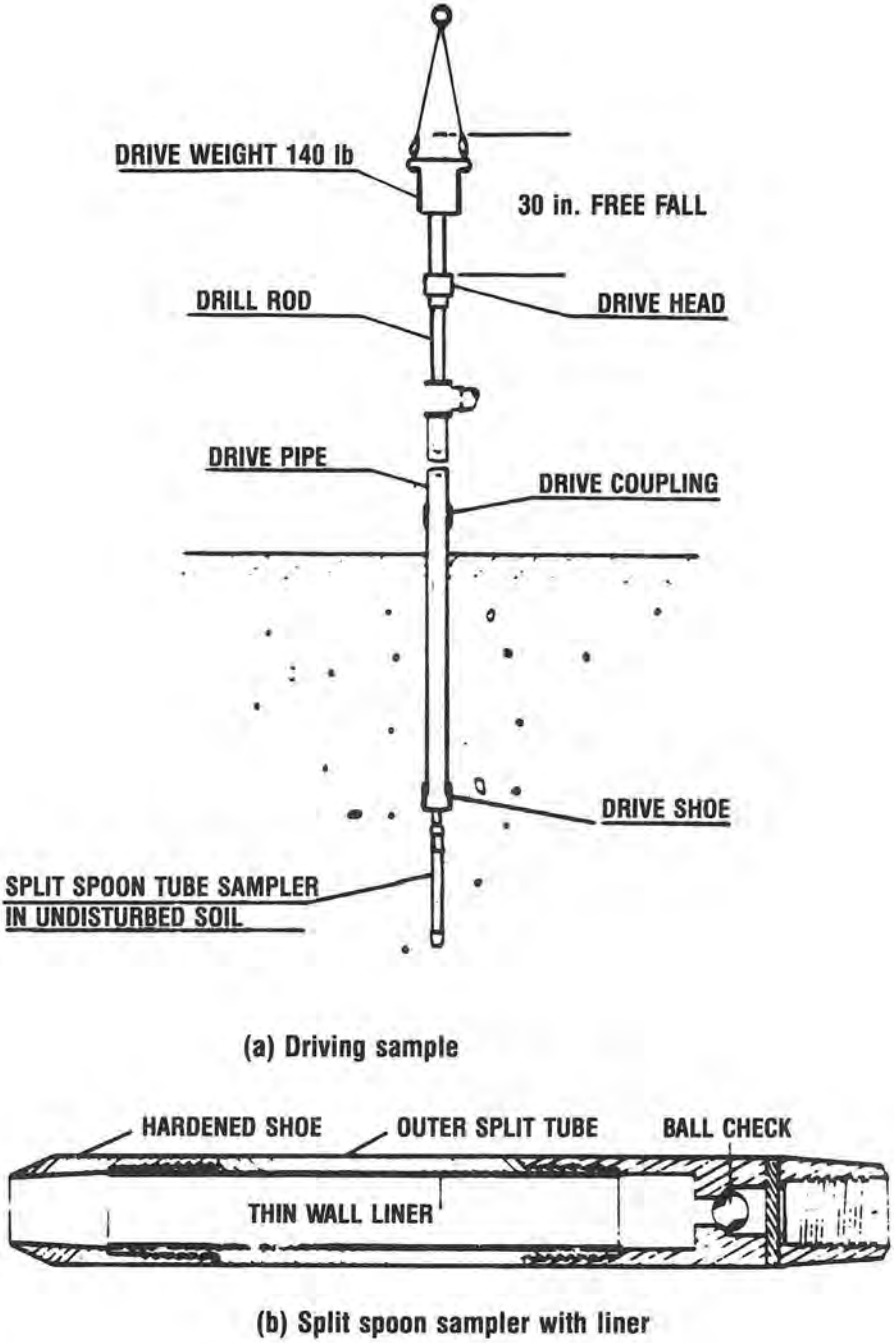


Figure 3.9 Split Spoon Drive Sampling Used for Detailed Exploration of Sand and Gravel Deposits[15].

Table 3.3 Rock Log Legend[18]

Rock Quality Parameters	
Grades of Decomposition	
D-1	Fresh Rock
D-2	Slightly Altered Rock (Joints Stained)
D-3	Moderately Altered Rock (Matrix somewhat weakened)
D-4	Highly Altered Rock (Matrix weak)
D-5	Residual Soil (Soil-like saprolite)
Grades of Strength	
S-1	Strong (Metallic sound, breaks with difficulty with hammer)
S-2	Moderately Strong (Dull sound; breaks with moderate hammer blow)
S-3	Weak (Cuts easily with knife)
S-4	Very Weak (Breaks with finger pressure)
Grades of Fracturing	
F-1	Massive (Fracture spacing greater than 3 ft)
F-2	Moderately Jointed (Fracture spacing 8 in. to 3 ft)
F-3	Very Jointed (Fracture spacing 4 in. to 8 in.)
F-4	Extremely Jointed (Fracture spacing 2 in. to 4 in.)
F-5	Crushed (Fracture spacing less than 2 in.)
Relative Hardness Scale	
Very Hard	Cannot be scratched with steel blade.
Hard	Scratches with difficulty with steel blade.
Moderately Hard	Easily scratched with steel blade, but not with fingernail.
Soft	Scratches with fingernail.

Rock Quality Designation (R.Q.D.) is based on a modified core logging procedure that, in turn, is based indirectly on the number of fractures and the amount of softening or alteration in the rock mass as observed in the rock cores. Instead of counting the fractures, an indirect measure is obtained by summing up the total length of core recovered, but counting only those pieces of core which are 4 inches (10 cm) In length or longer and which are hard and sound.

This procedure obviously penalizes the rock where recovery is poor. This is appropriate, because poor core recovery usually indicates poor quality rock.

A good relationship exists between the numerical values of the R.Q.D. and the general quality of the rock for engineering purposes. This relationship is as follows:

R.Q.D.	Description of Rock Quality
0-25%	Very Poor
25-50%	Poor
50-75%	Fair
75-90%	Good
90-100%	Excellent

Figure 3.10 summarizes the standard rock names and their graphic symbols. Colors used in descriptions should be in agreement with the standard reference colors guide.[19] Figure 3.11 is a typical form that can be used for core logging. In addition, logs kept by drillers should be retained because of their potentially important information. Sand and gravel samples usually are logged using standard engineering abbreviations and symbols (as shown in Table 3.4 and Figure 3.12). An example of a sand and gravel log form appropriately filled in is presented in Figure 3.13.

Correlating Units: After rock cores or sand and gravel materials have been logged, a geologist should be able to correlate the various rock types or sand and gravel zones between drill locations. When sedimentary rock is present, the layers or zones are defined as formations and/or members of formations or various subunits selected for the particular project. Metamorphic rocks usually have layers of distinctive rock types disclosed by the logging of cores. Igneous rock may have several rock types present that may be in irregular zones or in layers. Layering in sand and gravel deposits is usually very irregular and often there are no distinct units.

As a rule, the best way to determine how layers or zones are distributed through a deposit is to draw cross-sections and plot the positions, angle and depth of core holes along with the rock types encountered in each hole. Generally, described units can be correlated between drill sites and the subsurface distribution of various rock types can thus be determined.

Sampling Units: Sampling usually should be on a unit-by-unit basis and all of the material (or a longitudinal split core of the material) of a unit intersected by drilling should be sampled. Grab samples of cores, or any selectivity of materials from a sand and gravel deposit, can cause bias of samples and should be avoided.

The size of an individual sample is a function of the nature and number of tests, the condition of a core, including the angle of the beds or lines of weakness, and the gradation when sampling sand and gravel deposits. For a longitudinal split of a 2-inch diameter rock core, a suitable sample length is from 25 feet to 40 feet. When a homogenous rock layer is significantly thicker than 25 feet to 40 feet, the layer should be subdivided; when critical layers or units are less than this thickness, cores taken within the layer from two or more borings may have to be combined. When there are no distinct units as in some igneous rocks or some sand and gravel deposits, samples should be arbitrarily taken at a selected uniform interval such as zero to 30 feet, 30 feet to 60 feet, etc. In each case, the full interval should be taken for testing. Where a quarry exists, test intervals should represent the rock being quarried in each face.

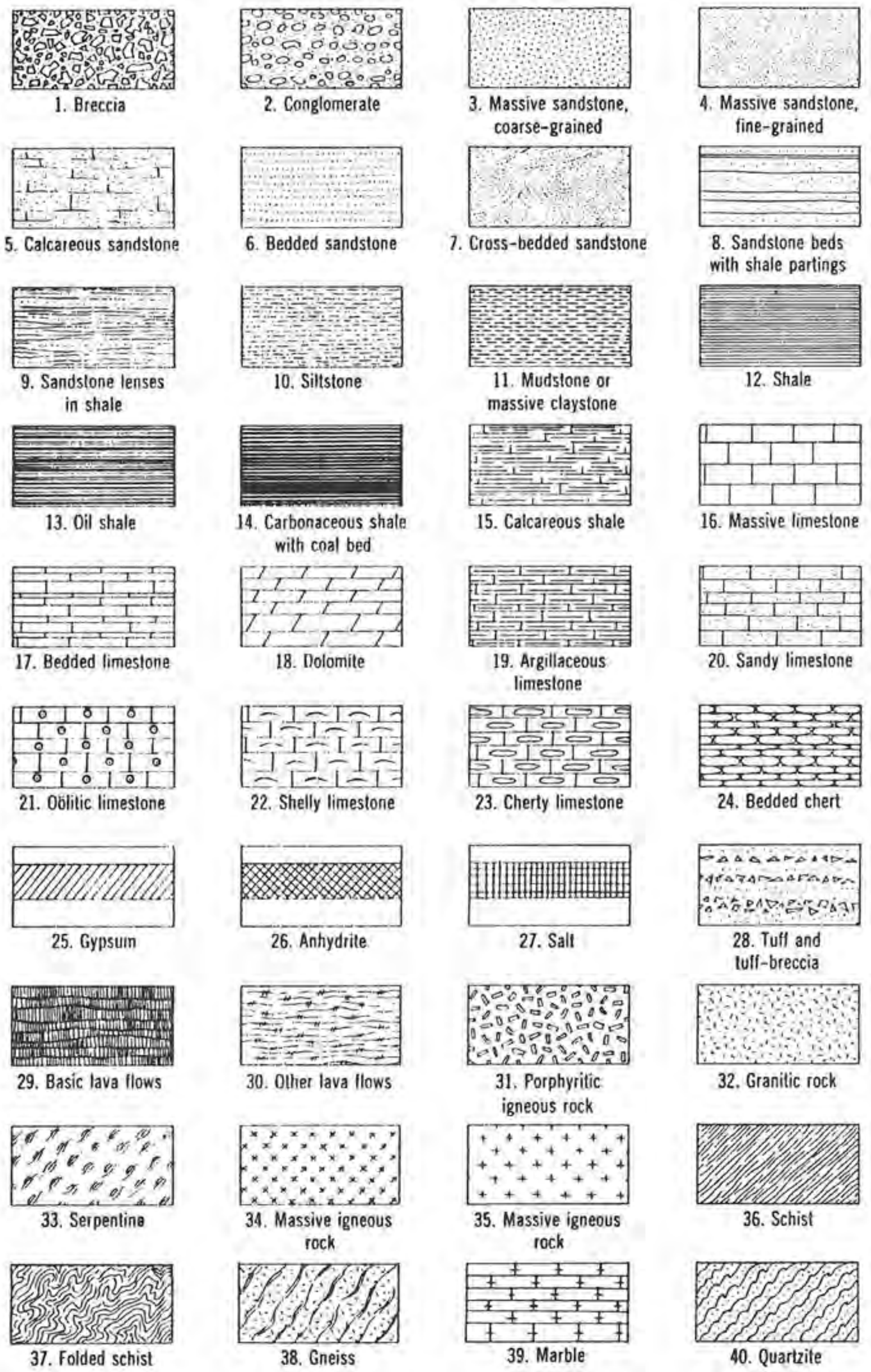
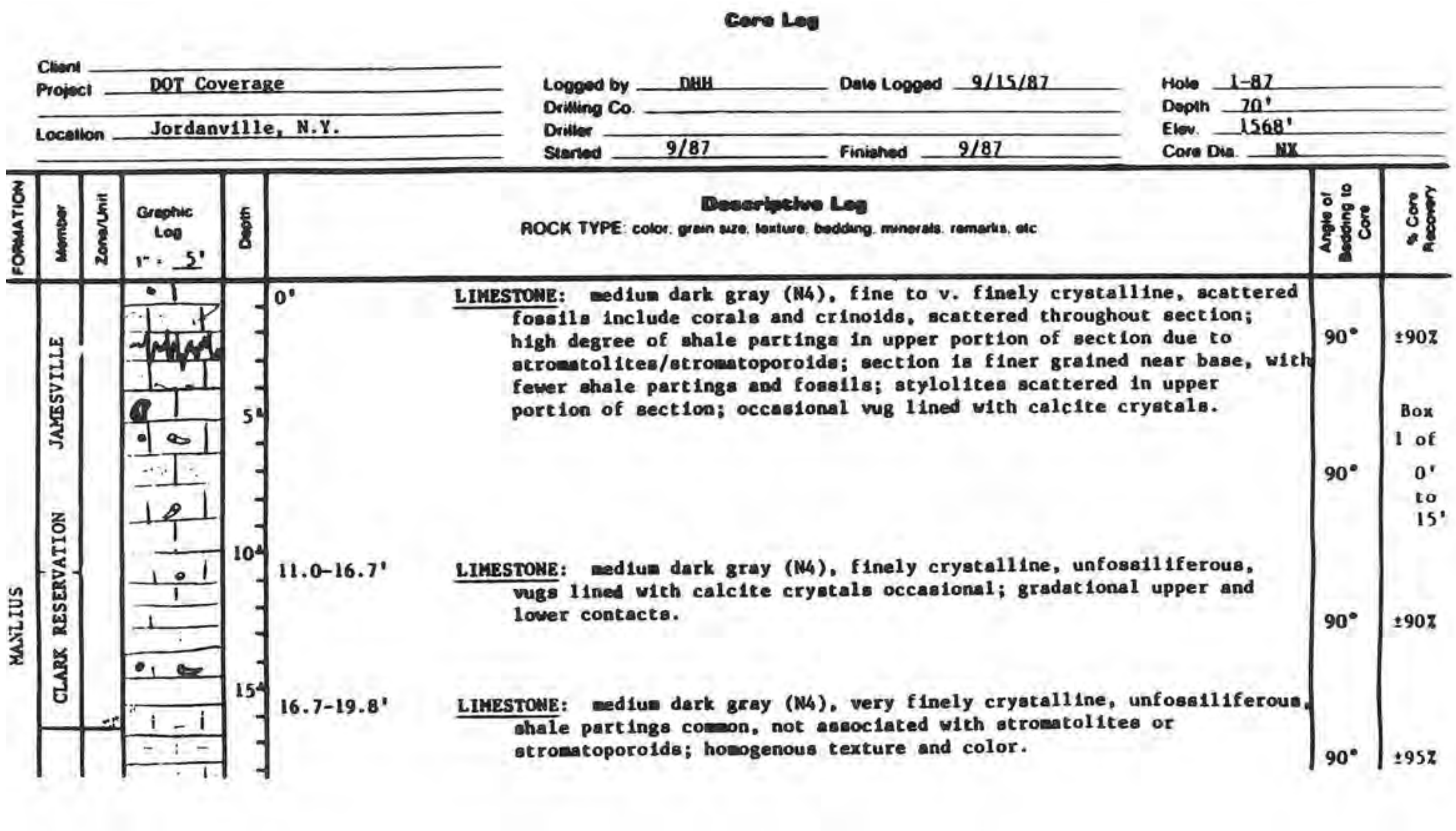


Figure 3.10 Standard graphic symbols used to describe rock[13]

Note: For unconsolidated materials the breccia symbol can also be used for overburden; conglomerate for sand and gravel; sandstone for sand; siltstone for silt; shale for clay.



Core Log

Client ______
Project DOT Coverage
Location Jordanville, N.Y.

Logged by DHH Date Logged 9/15/87
Drilling Co. ______
Driller ______
Started 9/87 Finished 9/87

Hole 1-87
Depth 70'
Elev. 1568'
Core Dia. NX

FORMATION	Member	Zone/Unit	Graphic Log 1" = 5'	Depth	Descriptive Log ROCK TYPE: color, grain size, texture, bedding, minerals, remarks, etc	Angle of Bedding to Core	% Core Recovery
MANLIUS	JAMESVILLE			0'	**LIMESTONE:** medium dark gray (N4), fine to v. finely crystalline, scattered fossils include corals and crinoids, scattered throughout section; high degree of shale partings in upper portion of section due to stromatolites/stromatoporoids; section is finer grained near base, with fewer shale partings and fossils; stylolites scattered in upper portion of section; occasional vug lined with calcite crystals.	90° 90°	±90% Box 1 of 0' to 15'
	CLARK RESERVATION			11.0-16.7'	**LIMESTONE:** medium dark gray (N4), finely crystalline, unfossiliferous, vugs lined with calcite crystals occasional; gradational upper and lower contacts.	90°	±90%
				16.7-19.8'	**LIMESTONE:** medium dark gray (N4), very finely crystalline, unfossiliferous, shale partings common, not associated with stromatolites or stromatoporoids; homogenous texture and color.	90°	±95%

Figure 3.11 Typical Core Log Form

Table 3.4 Glossary of Modifying Abbreviations (after the American Society for Engineering Education System)

Category	Symbol	Term	Symbol	Term	Symbol	Term
A. Borings	U/D	Undisturbed	B	Exploratory	A	Auger
B. Samples	C	Casing	L	Lost	U	Undisturbed
	D	Denison	S	Spoon	W	Wash
	O.E.	Open End				
C. Colors	bk	black	gn	green	wh	white
	bl	blue	or	orange	yw	yellow
	br	brown	rd	red	dk	dark
	gr	gray	tn	tan	lt	light
D. Organic Soils	dec	decayed	o	organic	veg	vegetation
	dec'g	decaying	rts	roots	pt	peat
	lig	lignite	ts	topsoil		
E. Rocks	LS	Limestone	rk	rock	Shst	Schist
	Gns	Gneiss	SS	Sandstone	Sh	Shale
F. Fill and Miscellaneous Material	bldr(s)	boulder(s)	cbl(s)	cobble(s)	gls	glass
	brk(s)	brick(s)	wd	wood	misc	miscellaneous
	cndr(s)	cinder(s)	dbr	debris	rbl	rubble
G. Miscellaneous Terms	do	ditto	pp	pocket penetrometer	ref	refusal
	el, El	elevation			sm	small
	fgmt(s)	fragment(s)	P.I.	Plasticity Index	W.L.	water level
	frqt	frequent			W.H.	weight of ham
	lrg	large	P	pushed pressed	W.R.	weight of rod
	mild	mottled				
	no rec	no recovery	pc(s)	piece(s)		
	pen	penetration	rec or R	recovered		
H, Stratified Soils	all	alternating				
	thk	thick				
	thn	thin				
	w	with				
	prt	parting	-0 to 1⁄16 in. thickness			
	seam	seam	-1⁄16 to ½ in. thickness			
	lyr	layer	-½ to 12 in. thickness			
	stra	stratum	-greater than 12 in. thickness			
	vvdc	varved Clay	-alternating seams or layers of sand, silt, and clay			
	pkl	pocket	-small, erratic deposit, usually less than 1 ft.			
	lns	lens	-lenticular deposit			
	occ	occasional	-one or less per foot of thickness			
	freq	frequent	-more than one per foot of thickness			

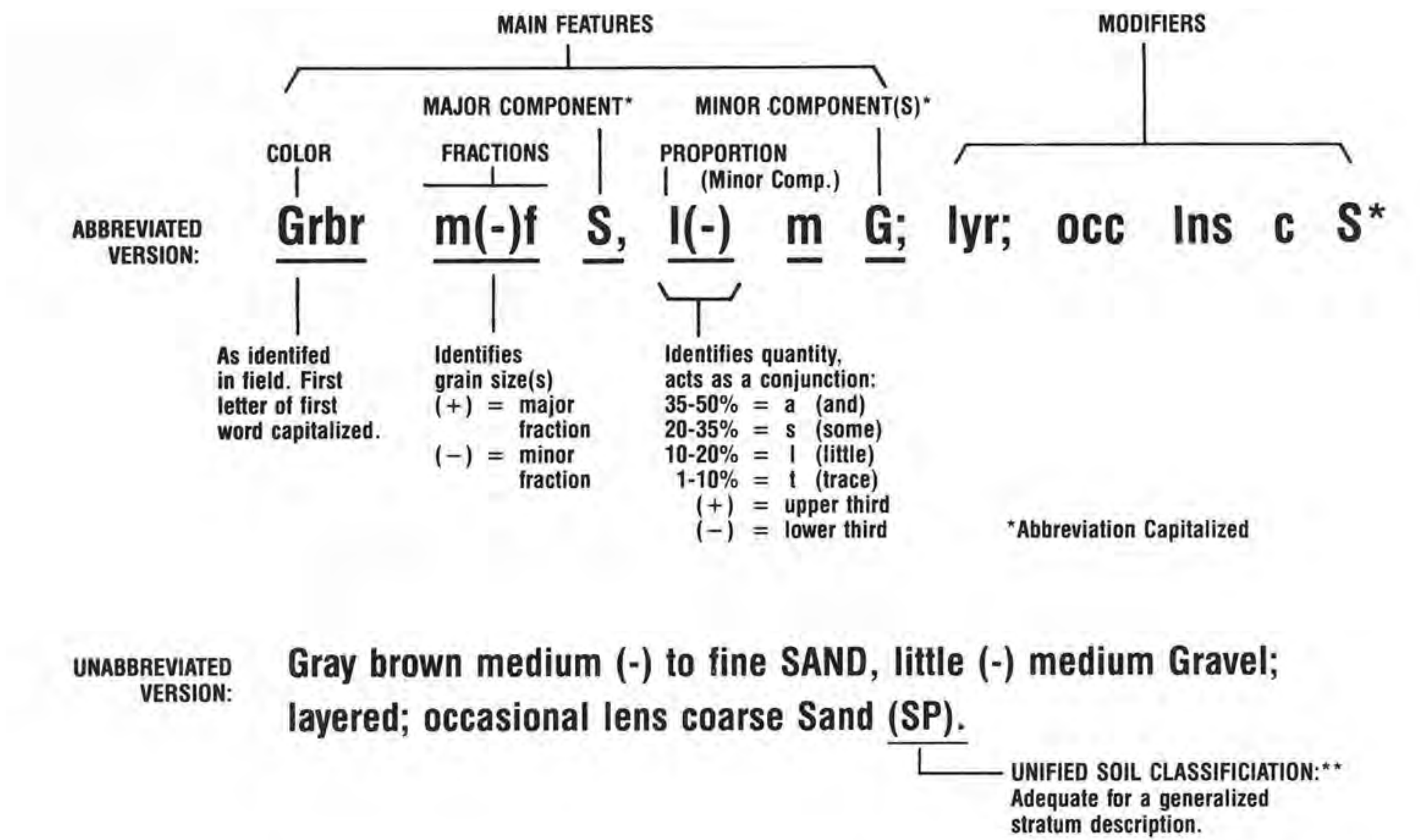


Figure 3.12 Modified *Burmeister System* for detailed identification of soil components, fractions, and proportions.

	Test Boring Log				Boring No. B89-1
Project :					Sheet 1 of 1
Client:					Job No. : 24-349-9-0006
Drilling Contractor:					Meas. Pt. Elev. : N/A
Purpose: Preliminary Site Evaluation					Ground Elev.: 577.0
Drilling Method: H.S.A.		SAMPLE	CORE	CASING	Datum: MSL
Drill Rig Type: Mobile B-47	TYPE	S.S.	N.A.	H.S.A.	Date Started: 5/5/89
Water Level: 2.3'	DIAM.	2"	N.A.	6-1/4"	Date Finished: 5/5/89
Measuring Point: Grade	WEIGHT	140 #			Driller: WJM
Date Of Measurement: 5/5/89	FALL	30"			Inspector: JEG

Depth (Feet)	Sample Numbers	Blow Counts	Unified Classification	Graphic Log	Geologic Description	Remarks
0	S-1	2, 7, 5, 6	SM		Gray brown coarse to fine SAND, little Silt, some fine Gravel. (FILL) 0.9' Gr gn $ l, f S	Rec=1.5' Moist Gravel angular N=12
	S-2	4, 5, 6, 7	SM		Gn gr f S Green gray coarse (-) medium to fine SAND, little Silt, some fine Gravel. (LACUSTRINE) 4.0'	Rec=1.9' WET N=11
5	S-3	5, 5, 7, 5	SW		Gr cmf S, t$, l mf G	Rec=1.7' WET N=12
	S-4	4, 8, 11, 15	SW		Gr cmf S, t$, s mf G Gray coarse to fine SAND, trace Silt, some medium to fine Gravel. (GLACIO-FLUVIAL)	Rec=1.7' WET N=19
	S-5	4, 7, 11, 15	SW		Gr c(+)mf S, t $, s mf G 10.0'	Rec=1.0' WET N=18
10	S-6	3, 4, 7, 9	CL		Dk rd $yC Dark red Silty CLAY. (GLACIO-LACUSTRINE)	Rec=1.6' WET N=11 Clay Stiff
	S-7	WR ↓	CL		Dk rd $yC 12.5' Brown red Silty CLAY.	Rec=2.0' WET N=0 Clay soft
15					End of Boring at 14.0' Backfilled with cuttings	

Figure 3.13 Sand and Gravel Log Form Using Data obtained from a Test Boring

The appropriate size of sample to be taken from an aggregates source can be determined from Table 18.1 in Chapter 18. When the aggregates consists of sand and gravel, with gravel as the minor component, samples in the range of at least 150 to 200 pounds should be taken if the quality of gravel is to be evaluated.

The person responsible for sampling also should be knowledgeable concerning the laboratory tests to be performed. Usually the first step of processing involves crushing and screening of material to provide appropriate gradation ranges for testing. Sieve analyses may involve a Gilson vibrating screen deck, if coarse aggregates sizes are involved, or a Rotap column of sieves if sand size particles are involved.[20] Following the screening operation, the sample may be reduced to appropriate size for individual test requirements using standard procedures such as those shown in Figure 3.14.[21]

Table 3.5, which is used by many mining geologists, contains suggested sample weights when the quantity of a very minor compound of a deposit must be determined as in the case of fibers or silica. Rock core samples (usually a half of split cores) should be retained in a safe storage area in the testing laboratory. Although sometimes difficult, storage of samples is worthwhile because reference samples can be very useful for later checking or for testing for purposes not initially visualized.

Table 3.5 Minimum Permissible Sample Weight at Different Particle Size (Modified from Mining Engineers Handbook)[22]

Diameter of Largest Piece		Very Low Grade or Very Uniform Ore. (1b)	Medium Ores. (lb)	Rich or Spotty Ores (lb)
In	Mesh			
4		4,800	35,564	
2		1,200	8,889	51,200
1		300	2,222	12,800
0.5		75	584	3,200
0.25		19	130	300
0.131	6	3.15	38.1	220
0.065	10	1.29	9.5	55
0.0328	20	0.322	2.37	13.76
0.0164	35	0.081	0.50	3.44
0.0082	65	0.020	0.15	0.54
0.0041	150	0.005	0.038	0.215

Overburden Analysis

Types of Overburden: Overburden is rock, soil or loose debris that is above the mineable aggregates resource and is of insufficient quality to process into construction grade aggregates.

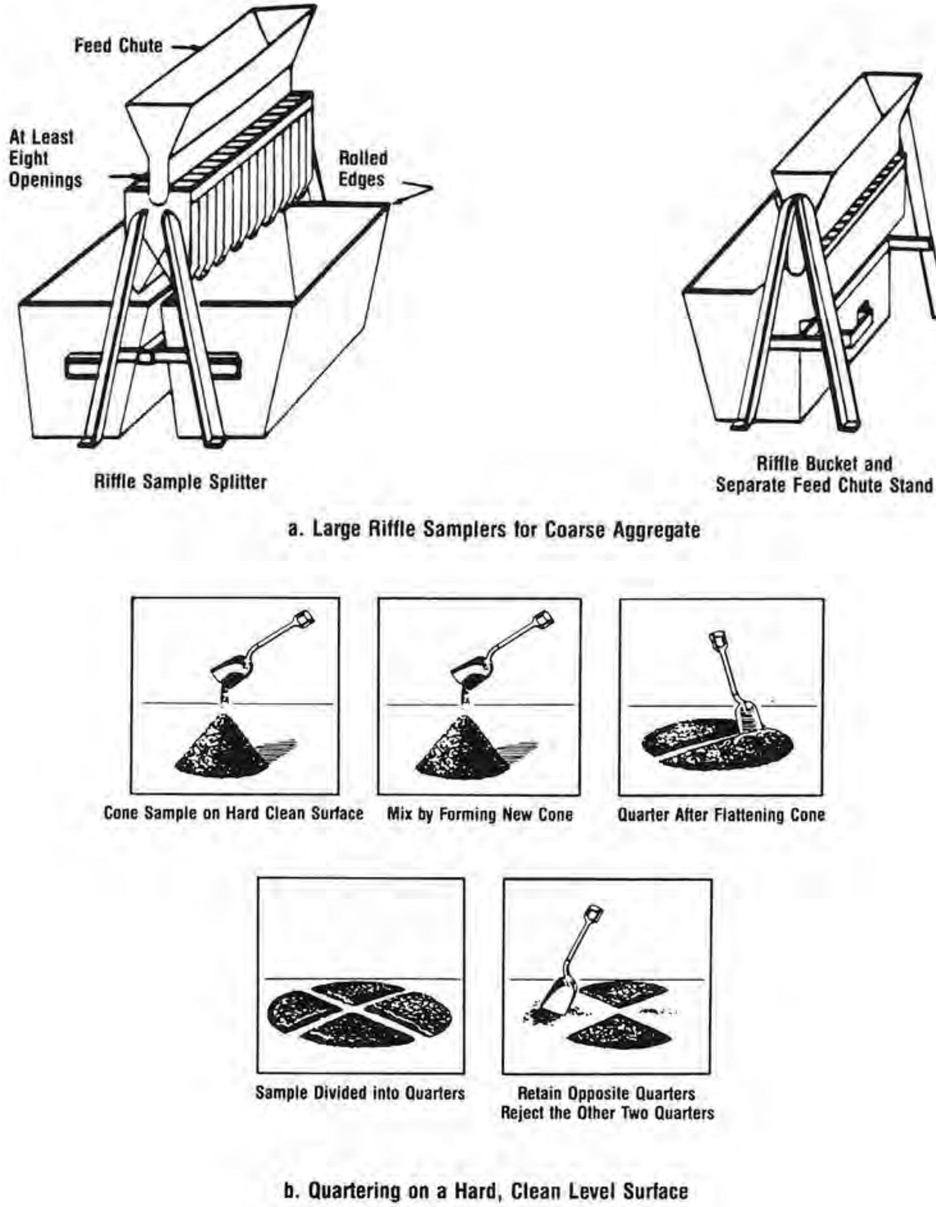


Figure 3.14 Examples of Sample Splitting Techniques.[21]

Overburden should be stockpiled for future reclamation but is sometimes wasted. The change from overburden to usable rock may be gradual as in many saprolites found in the southeastern United States. In these saprolites, the change from topsoil to high quality rock often goes through a zone where the materials have no value or where they can be employed only as fill or used in applications where low quality is acceptable. Overburden also may be rock of unsuitable quality for use as aggregates. Sometimes the overburden has irregular thickness and is difficult to evaluate or remove.

Measuring Overburden Thickness: The total amount of overburden should be determined because it usually must be disposed of somewhere on the property. The size and nature of the disposal area should be planned. In addition, the thickness of the overburden is important because excessive overburden can hinder excavation in some areas.

Generally, the quantity and depth of overburden is measured as a routine part of exploration drilling. The thickness and nature of overburden also can be determined through auger drilling, air track drilling or use of a backhoe depending on the particular conditions. Auger drilling can give misleading results when boulders are present, when deep weathering has occurred along planes of weakness of the rock, and when deep layers of partially weathered rock are present.

When the thickness of the overburden is highly variable, geophysical methods of exploration are a valuable supplement to drilling. Seismic, resistivity, electromagnetic, and radar techniques, or even other methods, are applicable in some situations depending on the specific site conditions.[23] Geophysical techniques are applicable when measurable physical contrasts exist between rock and/or soil types. For example, seismology is applicable when there are measurable differences in sonic velocities of different materials; resistivity when measurable differences exist in electrical conductivity; electromagnetics when there are differences in electromagnet response; radar when penetration and reflectivity of ultrasonic waves is variable, and so on.

Isopach maps, in which the thickness of overburden is plotted as equal-thickness contours, may be valuable for some deposits.

Calculating Reserves

Once the nature and distribution of economic aggregates resources have been determined, the volume and tonnage of these *reserves* are estimated.

Volumes: Calculations to determine the volume of aggregates reserves for simply layered rocks may be as easy as multiplying the thickness of layers by the area occupied by those layers. When thicknesses are highly variable, several other techniques are used:[23]

1. *Adjacent Cross Sections.* Vertical geologic cross sections are drawn at regular intervals through a deposit and the cross-sectional area of the deposit determined for each section. Volume is determined by multiplying the average area of the resource for adjacent sections by the perpendicular distance between the sections.

2. *Tributary Area.* Volumes can be calculated using the area tributary for each drill hole. The tributary area is defined as extending half way to each adjacent drill hole. The local thickness of the deposit is then taken as the average between adjacent holes. The average thickness for the resource for each block is taken as the average of those measurements, and the volume

is this average times the area of the block. Figure 3.15 illustrates some of the patterns and methods that are used for estimating reserves.

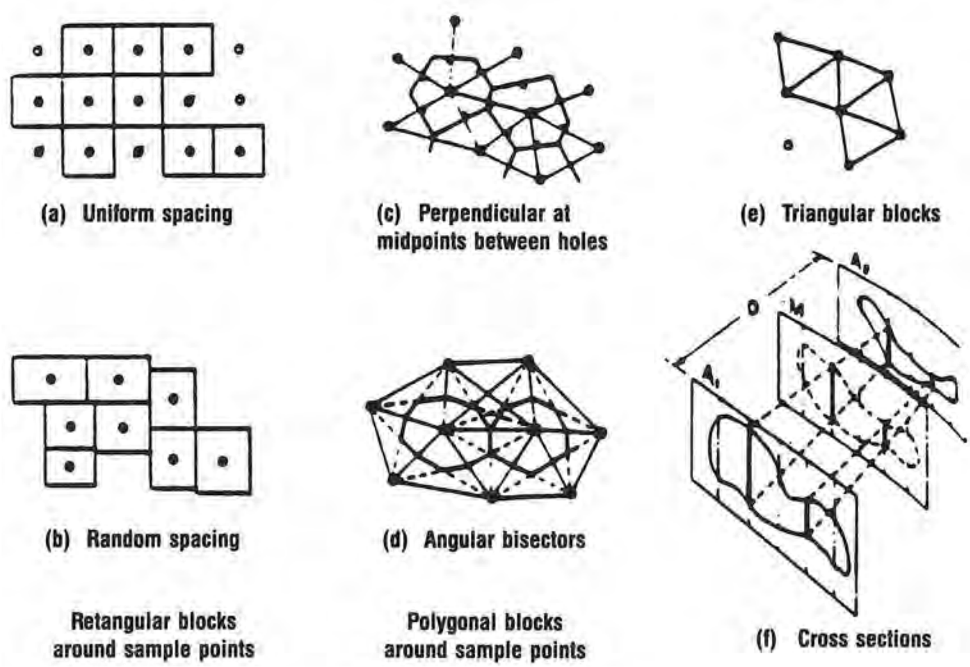


Figure 3.15 Commonly used geometric patterns for ore-reserve calculations.[23]

Tonnage: For crushed stone, the tons of reserves are calculated by multiplying the weight of usable rock per unit volume times the estimated volume. Usually volume is in cubic feet or cubic yards and the unit weight is in pounds per cubic foot or it may be a specific gravity (sg). Specific gravity is the weight of a given volume of a material divided by the weight of the same volume of water. Some typical specific gravities for common raw rock (aggregates) are given in Table 3.6.

Table 3.6 Typical Variations of Specific Gravities of Selected Common Rock

Rock Type	Specific Gravity	Rock Type	Specific Gravity
Andesite	2.4 to 2.8	Granite	2.6 to 2.7
Basalt	2.7 to 3.2	Limestone	2.7 to 2.8
Trap rock	2.8 to 3.1	Marble	2.6 to 2.9
Dolomite	2.7 to 2.8	Sandstone	2.0 to 3.2
Gabbro	2.9 to 3.1		

To obtain the in situ tonnage of a reserve knowing the specific gravity and volume of the usable rock, the following equations are used:

$$\text{Yield (ft}^3\text{ / ton)} = \frac{2{,}000}{64.4 * ¥\ \text{sg}} \tag{3-1}$$

$$\text{Reserve Tonnage} = \frac{\text{Voume of Reserve (ft}^3\text{)}}{\text{Yield (ft}^3\text{ / ton)}} \tag{3-2}$$

** Weight of water in pounds per cubic feet.*

The *usable tonnage* is the in situ reserve less the unrecoverable material from buffer zones, pit slopes, waste, haul roads and ramps.

For sand and gravel deposits, calculating the number of cubic feet per ton is somewhat more complicated because of variations in the degree of packing and of water content. Some typical unit weights of sand and gravel deposits are summarized in Table 3.7.

Table 3.7 Typical Unit Weights of Sand and Gravel

Aggregates	Pounds per Cubic Foot
Sand and Gravel	
Dry	108
Wet	125
Compacted (with clay)	140 to 150
In situ (dry)	117 to 135
Sand	
Loose dry	100
Slightly damp	120
Wet	130
Wet packed	130

Because of the large variation in the specific gravity of sand and gravel deposits, for ease of calculation the unit weight is sometimes assumed to be 111 pounds per cubic feet (1.5 tons per cubic yard). If a more precise in situ measurement of unit weight is required, a small hole can be dug into the deposit and the aggregates removed and weighed.[24] Then the volume of the hole is determined by lining it with plastic and filling the plastic-lined hole with water. The weight of water in the hole can be used to obtain the size of the hole. The wet unit weight of a material (Y_{wet}) is then equal to:

$$Y_{wet}\ \text{(pcf)} = \frac{\text{Wet weight of material removed (lb)}}{\text{Weight of Water to Fill Hold (lb)}} \times 62.4\ \text{lb / cu ft} \tag{3-3}$$

The dry unit weight (Y_{dry}) of the material that usually is significantly less than the wet weight can be obtained as follows:

$$Y_{dry} = \frac{Y_{wet}}{1 + w} \qquad (3\text{-}4)$$

where the wet unit weight (Y_{wet}) is determined from equation 3-3 and "w" is the water content of the soil. The water content (w) is determined from the sample of material removed from the hole. The water content is the weight of water in the sample determined by drying the sample at 105° F divided by the weight of dry solids. Usually water content is expressed as a percent, but when used in equation 3-4 it is left in decimal form.

Nature of Reserves

Introduction: The quantity and quality of resources, referred to as reserves, should be assessed at all stages of exploration of a property. In the early stages, before any significant sampling or testing has taken place, reserves only can be implied and generally are placed in the category of possible or inferred reserves as discussed below. Before any significant investment is made in terms of time, money, permitting, etc., a determination of the reserves is needed. How much information is required about reserves is a function of the purpose for which the estimation is being made. For example, the purpose may be to obtain enough information to justify the expense of obtaining permits to operate. Alternatively, the reserve information may be used as a basis for investment in the land, plant or for a bank loan. Overspending or under-spending on reserve analyses frequently occurs.

Probability Classification: The generally accepted reserve categories are summarized as follows:[25, 26]

1. *Proven Reserves*. *Proven reserves* are interpolated using closely spaced drilling from which rock or sand and gravel samples are obtained. Proven reserves are sufficiently understood so that the grade, quantity and engineering characteristics of the resource at any random point within the proven block are known sufficiently accurately to be mined without need for any further work. Typical drilling spacings for stone deposits should be less than 200- to 400-foot centers; for sand and gravel 200-foot centers often are used. Actual required spacing is based on geologic judgment about the predictability of continuity of critical characteristics of each deposit.

2. *Probable Reserves. Probable reserves* also are interpolated between sample points, but the points are too widely spaced to allow detailed prediction of quantity, quality and/or engineering conditions. Probable reserves are interpolated with the justification for their continuity being based on geologic judgment. Typical sample point spacing is likely to be twice that required for proven reserves.

3. *Possible Reserves. Possible or inferred* reserves are quantities of reserves that are extrapolated beyond the sample points based on geologic judgment.

3. *Investment Reserves.* This category is defined as reserves that are sufficiently known to justify further investment in land or physical plant or to justify a loan from a lending agency. The reason for this new classification is that it may be difficult for a bank or a board of directors to justify investment in an operation based on the probable reserve category. However, for all reserves to be proven reserves in the classic sense is usually prohibitively expensive and totally unnecessary at an early stage of evaluation. In other words, ample justification can exist for investment even though the reserves are not proven in an engineering sense.

The above classification for reserves is related to the degree of certainty of the reserve figures. Such reserve figures, taken alone, are not usually a sufficient basis for making economic-engineering decisions. The primary problem is that the purpose of the above reserve classification is often to classify an area's or a nation's reserves for planning purposes. The purpose that a company has for classifying its reserves may be somewhat different. Hence, the standard classification of reserves is not wholly applicable to the needs of mining companies.

Recoverability Classification: The degree of certainty is only one component of the definition of reserves. Usually reserves should be classified further in terms of recoverable or marketable quantities before major investment decisions are made.

1. *Gross Reserves. Gross or geologic reserves* are the total reserves under a property regardless of their recoverability or their marketability.

2. *Recoverable or Mineable Reserves. Recoverable or mineable* reserves are those reserves that can be removed from the ground. Examples of materials that are not mineable are those that must be left in safety benches and berms in quarry operations; in pillars in an underground operation; or reserves that may be inaccessible due to engineering limitations such as excessive depth, water conditions or excessive overburden.

3. *Net Reserves or Marketable Reserves.* This category of reserves is that component of a deposit that actually can be marketed. For example, stone processing creates fines that may not be marketable; sand and gravel deposits usually contain unmarketable clay and silt within the deposit and additional fines are created by abrasion as a result of processing. Losses of this type may run from 5 percent to 20 percent or more and usually should be subtracted from mineable or recoverable reserve figures.

Example Classifications: Examples of reserve classifications are *gross probable, proven net or proven recoverable*. Often the category of reserves is not clearly stated in a report. In all cases, the method of calculating reserves should be described in a report so that a company always knows how much product actually can be recovered and sold. This is true whether an operation is mining aggregates, gold or coal. Finally, all reserve categories can change during the course of mining because of changes in geologic knowledge, regulations, demand, equipment, planning, engineering or other factors.

Required Amount of Reserve Information: The amount of information required about reserves is dependent not only on the purposes and stage of exploration as noted above but also upon the following additional factors:

1. *Magnitude of an Investment.* Generally, greater investments require more data.

2. *Anticipated Rate of Production.* The production rate is partially related to the first item because higher rates of production usually imply larger investments. Generally, a higher production rate requires more testing simply because more reserves are required for higher production.

3. *Anticipated End Use of the Resource.* Stone deposits utilized additionally as raw material for portland cement or agricultural limestone require chemical testing to assure compliance with quality requirements.

4. *Complexity of the Resource.* Sources of aggregates may be complexly folded and/or faulted, may change rock type rapidly or may include irregular clay zones. When such complexities exist, more testing is required than if, for example, the rock is horizontally layered and known to change little over wide areas.

Reserves and Permitting: A frequent and difficult judgment to make is how much reserve information is required before seeking a permit to operate. The permitting process is very expensive because it involves the costly time of lawyers and consultants. Enough reserve information should be obtained to satisfy the minimum requirements of the permitting process and of the environmental impact statement if one is needed. The greatest risk to an operation becoming viable is often due to the uncertainties of the permitting process. Therefore, expenses in advance of this process should be held to a minimum. Conditions can exist where the demands of the permit require costly reserve analyses, engineering planning, market analyses and transportation studies. The producer often must look at the money spent in advance of permitting as risk capital that is invested in the probability of obtaining a mining permit. This single risk may be greater than all other normal risks inherent in the production of aggregates.

3.7 Rock Quality Issues

Changes by state agencies such as Departments of Transportation (DOT) in the rock quality properties tested to establish if the rock is acceptable affect the rock types selected for mine exploration and development. For example, the sulfate soundness test (ASTM C 88; AASHTO T-104), previously used in many states is being replaced (particularly in the midwest) by the Standard Test Method for Resistance of Concrete by Rapid Freezing and Thawing (ASTM C 666; AASHTO T-161). This change in durability testing procedure has resulted in some rock types previously acceptable under sulfate soundness specifications not being approved by state DOTs for concrete aggregates use. *Therefore, at the early stages of an exploration program a meeting* *should be held with state DOT officials to discuss rock quality approval requirements, including possible future changes, and their impact on potential resources and future plans.*

3.8 Exploration and Evaluation of Potential Reserves

Environmental and Zoning Constraints

Exploration and evaluation of potential aggregates deposits require more than knowledge of geology and the aggregates business. *Environmental laws and regulations must also be understood.* Wetlands, for example, are not only regulated at the federal level, but also at the state and local level in many locations. The maze of complex regulations, which often are conflicting, might lead to the conclusion that an otherwise acceptable aggregates site containing extensive wetlands does not deserve further serious consideration. Other environmental and social conditions also must be considered early in the exploration process including air and water quality, zoning and nearby land use. A visit to a local planning agency sometimes can quickly identify existing sensitive technical and social issues. Environment laws, regulatory compliance and community relations are discussed in detail in Chapters 4 and 5.

Drilling, Sampling and Testing

Determining the appropriate amount of drilling, sampling and rock quality testing of a potential aggregates source always is difficult. The explorer must determine the quantity of reserves necessary to justify possible future investment in the site including its development. Drilling and rock quality testing should be concentrated in an area that is large enough to provide minimum required reserves with a reasonable level of certainty. Sufficient additional testing also should be performed to allow projection of reserve quantity and quality adequate for future development planning. Future drilling and testing programs should also be required to follow this approach. Likewise, the depth of a drilling and rock-testing program should be designed with possible quarry *depth constraints* in mind. Quarry depth constraints are based on formation thickness (obtained from geologic literature or preliminary drilling results), water table information, regulatory restrictions and practical mining considerations.

When performing a subsurface exploration program, developing detailed information about *hydrologic* (i.e., groundwater) conditions is often as important as obtaining information concerning the rock itself. A simple well test using compressed air to blow water out of the drill hole for a period of time, and then measuring the recovery rate of the water level provides valuable information about the yield of water from the geologic formation and about future mining conditions.[7, 8] Also, one or more drill holes can be simply and inexpensively converted into water table observation wells. These observation wells give valuable information concerning groundwater levels, fluctuations in water levels and the slope of the water table across an area, also called a *hydraulic gradient*. Detailed information on geologic formations, rock quality, variations in both quality and hydrologic conditions are necessary for the development of realistic mining and reclamation plans.

3.9 Summary

Software packages that provide powerful analysis capability for all aspects of mine development are available usually at modest cost. The use of carefully chosen software gives important insights into mine development that would be too time-consuming to achieve using hand calculations. During the early stages of mine development, meetings should be held with appropriate government agencies that write material specifications to discuss rock quality approval requirements and possible future changes in these requirements.

The occurrence of subsurface water and its variation with location and time is important in mine development. Hence, site exploration for a mine must include a thorough study of the hydrologic conditions. Governing environmental laws and regulations in mine development are also just as important as geologic and engineering considerations. Finally, an early visit to local planning agencies can often identify existing sensitive local issues.

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Chapter 4
Environmental Compliance

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4.1 Introduction

This chapter provides an overview of the environmental concerns associated with the design, development, operation and closures of non-metallic mineral mines, which includes aggregates mines (sand and gravel pit or bedrock quarry). The focus is on the regulatory and voluntary aspects of zoning, permitting and operating the aggregates production facility and suggested guidelines for responding to community concerns based on the public's historical misconceptions of the mining industry and lack of understanding of the aggregates industry in particular. Environmental issues addressed in this chapter include: 1) mining permits, 2) land quality, 3) surface water quality, 4) groundwater, 5) air quality, 6) waste management, 7) management of petroleum and other substances and 8) environmental management systems.

4.2 Mining Permits

Although the initial decision to locate a mine is based on the physical presence of a reserve, a local market for the product and the economic viability of extraction; the zoning and permitting processes can place significant restrictions on aggregates mining. The specific requirements for mining permits vary with location and may be controlled by local municipal (city or village), township, county or state ordinances, laws and rules. In general, the aggregates industry is heavily regulated with permit requirements typically related to land use, operational factors, safety, air and water quality, blasting, noise, product transportation and other factors.

Mining is a unique industry. It is a heavily regulated industrial business and as such, mining operations must adhere to federal and state regulations regarding the environment in addition to the mining-focused regulations of the U. S. Mine Safety and Health Administration (MSHA) and closely regulated rules concerning the handling and use of explosives. Somewhat unique to mining is the extent to which local demands can place the most stringent requirements on a mining operation through the local permit to operate; conforming use, conditional use, special use permit, mining license or a variety of other names; that are often requirement of local government (in some cases states) that must approve the mining operation.

The locally obtained permit to operate a mine is a business outcome often determined by public opinion versus rules and regulations. Rules can be dissected and obligations checked off line by line. Public opinion is based on risk perception, personal biases, emotion and fear, and education. Public opinion also is often provided in writing in the form of letters, emails, blogs, newspaper editorials and interviews, but it is most powerfully delivered in emotion-filled hearing rooms during public hearings that often precede an agency decision on whether or not a permit to operate is granted and under what conditions. Public opinion can be countered to a degree with technical facts, but opinion is neither right nor wrong and as such, a technical expert must take great care in handling opposing opinions.

Public opinion for or against a mine is influenced by many factors that vary by area; some examples of these factors are demographics, historical performance and relationship of mining to the community; physical factors of the mine such as size, truck traffic, etc. Factors such as population density and long- and short-term residency also can play a role in affecting public opinion. The aggregates industry now needs to address an increased level of public sophistication, education and access to information. One can do an Internet search as simple as "how to fight a mine" or any number of similar searches to find all the common arguments that local opposition groups may use against the mining industry.

Although the level of public sophistication, education and access to information is greater than it has ever been, aggregates mines are increasingly becoming encroached upon and surrounded by residential neighborhoods. It is these same people who will fight the mine's expansion. The public's education concerning the uses and need for aggregates is being overlooked. This is a longstanding industry issue that slowly is being addressed. For example, the importance of mining to a community is stated very well in the Wake County, N.C., Annotated Zoning Ordinances dated December, 1985, as follows:

"Extraction of mineral resources is a basic and essential industry which plays an important part in the Wake County economy. While mining crushed stone is presently the most important mining activity in Wake County, other mineral products can become important to the economy of the county. Mining is a peculiar land use in that the location of mineral deposits will, in part, be determined only after exploration and discovery in the future. Consequently, the precise location of a zoning district wherein mining may take place cannot always be predetermined. Mineral extraction involves several methods: quarrying, open-pit, drilling, tunneling, etc., each of which would affect a neighborhood environment differently. "

Therefore, the Board of Commissioners of Wake County concluded that extraction of mineral resources should be encouraged; fundamental purposes and procedures of zoning would be served best by adoption of general regulations governing mining, which apply to all use-specific districts; and the commissioners should consider each location proposed to be mined to determine whether and under what conditions or safeguards they should authorize mining by the issuance of special use permits.

4.2.1 Land Use Requirements

In most states, mining is a local land-use issue and as stated above, the specific requirements for mining permits will be controlled by the municipality, township or county. Land must either be zoned specifically for mining or the zoning must include mining as a conditionally permitted use. Land with zoning that does not include mining requires a zoning change process to rezone the land. Only then can the condition-use or special-use process to obtain a mining permit be pursued.

There are many obstacles to overcome in the process of obtaining favorable zoning, including comprehensive land-use plans that do not appropriately address aggregates mining and sometimes specifically exclude it, current and future land use, commercial and residential encroachment on existing mines, local or community opposition related to operational or technical factors of existing mines and real estate developers and even competitors in the mining business.

The aggregates industry, and mining industry as a whole, is facing an increasing challenge developing suitable new aggregates resources. The public has an understandable desire to protect the environment and the perception that mining is not compatible with other land uses is difficult to overcome. As a result, successful zoning changes and mining permits are increasingly challenging to obtain. The aggregates mining industry continues to make significant progress towards improving public image and perception through efforts such as the NSSGA's Awards Programs that include recognition for member efforts to improve community relations, the environment, worker safety and health and commitment to the industry and community.

4.2.2 Zoning and Local Ordinances Regarding Mining

Local governments and citizens are interested in promoting the health, safety and general welfare of the community. Zoning regulations usually are established in accordance with a comprehensive land-use plan. They are designed primarily to manage urban sprawl, control land development and protect recreational and agricultural resources. In addition, the comprehensive plans may address public safety, health and infrastructure such as transportation, water, sewer, schools and parks. Zoning regulations are developed to consider the character of the jurisdiction, the suitability for particular uses; the conservation of the quality and value of structures and public infrastructure, and to encourage their most appropriate use.

The land-use permitting and zoning requirements vary significantly as the requirements are determined based on state and local regulation, statutes and land use plans. As such, when planning to permit a new aggregates mining operation or expand an existing operation, having a good understanding of the processes and stakeholders involved is necessary to project timing and cost of the process.

In some areas of the country, such as California, the permitting process may take several years. The costs often are extensive and a successful result is not certain. Universally, the general trend in land-use planning involves tighter control and greater restrictions to development. As a result, the effort and time required to obtain a permit is increasing resulting in extensive pre-permitting review before a mining operation is permitted.

Local zoning boards and commissions developed to regulate zoning are in place in most states and generally consist of an elected body comprised of a local board of commissioners or city council. The elected officials and bodies will appoint additional bodies such as a board of adjustment, board of appeals, planning committee, land management committee, etc. The zoning authority and its appointed bodies also have support such as legal counsel, municipal or county manager and technical staff.

The enforcement of local and county ordinances usually is left to a zoning administrator, with responsibility for review of permit compliance through review of required submittals and conduct of investigations when there are complaints. Non-compliance or violation of a permit condition will put the permit at risk either immediately or at the time of permit renewal or request for permit modification.

4.2.3 Obtaining the Conforming Use/Special Use/ Conditional Use Permit

In the early stages of developing a permit application, it is important to understand the ordinance, the process, and the decisions shapers, and identify the decision makers. The ordinance should be dissected and every aspect understood. An approach should be prepared to properly address each requirement. It is essential to understand the decision shapers, who they are, what their goals are and how they may help or hurt the chances for obtaining a permit to operate. Also, get to know the decision makers, who they are, what their views are, their record on decisions made that affect the aggregates industry and, where applicable, their election or appointment cycles.

The local permit to operate is commonly referred to as a conforming-use permit, conditional-use permit, special-use permit, mining license or variety of other names and is typically provided by the local unit of government. The requirements needed to obtain such a permit are commonly defined in the applicable ordinance and are allowed where the zoning designation allows for such permitted uses or after a petition for variance is approved by a board, council or other applicable unit of government. A permit application review is undertaken by the governing authority to evaluate consistency with the zoning designation and that the proposed use will not cause undue harm or hazards. The requirements of permit application content will vary and be defined either specifically or generally in the applicable ordinance. It is the obligation of the permittee to provide as much information as possible in the application process to minimize review time and avoid repeated submittals.

Typically, permitting will include the public hearing process at the local level of government, either municipal or township and, depending on jurisdiction, appearing before the applicable land management unit of government at the county level. Each unit of government will have input into the conditions of the permit so complete detailed preparation is critical and recommended at every stage of the process. With a strong technical team and thorough understanding of the ordinance, the public hearing process should be an opportunity for the permittee to be proactive and drive the process versus the untenable position of being reactive, defensive, not in control and appearing not to understand the ordinance or the needs and desires of the local citizens.

Develop a Strong Technical Team

Build a strong technical team to develop and support the permit application process. Know the difference between a strong technical team and "hired guns." Individuals with a reputation as a hired gun will use their experience, education and demeanor to make convincing public arguments for or against an issue and will show little if any allegiance to their profession or the mining industry. Such individuals, for a fee, will be pro-mining one day and anti-mining the next, and are disparaged by most dedicated mining professionals.

A strong technical team should consist of company resources supported by consultants, especially those who have demonstrated a commitment to the mining industry. Company resources include management, public relations, marketing, engineering, environmental, safety, human resources, sustainability, drilling and blasting, logistics and operations. Outside consultants include mining, geotechnical and structural engineers; geologists/hydrogeologists; environmental experts in surface water, groundwater, air, aquatic resources, wildlife and reclamation; safety and health professionals, such as industrial hygienists and toxicologists; traffic; real estate; economic impact analysts; legal counsel; and others as unique situations may require.

Understand the Decision Shapers

There are many decision shapers who will influence and impact the permitting process. These include local non-governmental organizations (NGOs) that may have an interest in local natural resource habitats or ecosystems or future potential ecosystems and, as such, may have interest and influence on the mine reclamation plans. Citizen, community and other various ad hoc groups may pre-exist or form for or against the mine. Groups that may support a mine include economic development, chamber of commerce, local labor groups, unions, etc.

Groups that are against mining often are lead by activists from inside the community, but outside groups also travel will to support an anti-mining campaign. Such anti-mining groups will include individuals that do not want mining in their neighborhood, do not like mining for various reasons do not understand the importance of mining and believe that mining is simply not needed anywhere.

There are also decision shapers that are neutral and often will remain so unless compelled for some reason to support, fight against or simply abstain. Such groups include NGOs involved with watershed protection, land or ecosystem conservancy or stewardship, etc. Aggregates mining operations can offer a unique combination of resources to support these groups that includes material resources such as rip rap, crushed stone, sand and gravel; but also heavy equipment and labor to support construction and restoration projects.

Understand the Decision Makers

As previously referenced, there are several groups of decision makers who are involved in the mine permitting process. These include a variety of municipal, township and county committees, commissions, councils and boards. Each state, county and local municipality has its process and people assigned to make the decision concerning a mine permit. Success in gaining a new mining permit will be improved if the process and the people are known. Review the names and addresses of the decision makers.

Taking the time to know the local culture will provide benefits. In rural communities, study the maps; drive the roads; get a feel for the traffic; see the land use; read the business and farm signs; recognize the names of roads, streams and other local landmarks; spend time in the local establishments and attend local public functions. All these observations will influence how a permit application is prepared and potentially accepted during the local review process. As you drive those local roads, be conscious of the affect your proposal will have on decision makers who live in that community. Also, it is important to recognize those road, farm, business and landmark names as they compare to the names and addresses of the decision makers.

It is beneficial to know the key decision makers, views on the public process. Some are not swayed by public opinion and are concerned only with due process and the basis of their decision is in the law. Others may give the highest regard to public opinion and allow the turnout at public hearings, petitions and letters to have the greatest impact on their decision. Where applicable, knowing the history of decision makers on related matters is beneficial and knowing the election cycle and public perception of individual decision makers can influence when a permit application is submitted.

Communication is the key; maintain active and frequent contact and communications with key decision makers and work to gain their support. Know where the decision makers stand before they vote on the permit application. If the support is not there prior to a decision making hearing or meeting, table the proposal and work to build the support that is needed. Be ready for compromise and understand how much flexibility you have on any issue that is anticipated to be a concern.

4.2.4 Mine Permitting Concerns

Pursuing a permit to operate requires an understanding of the concerns of the decision shapers and the decision makers. Recognize that the basis of opposition to mining almost always stems from a concern over a perceived risk or threat to something that is highly valued such as harm to public health, disturbing the quality of life, damaging the environment, ruining the drinking water supply, destroying the local landscape, etc. Whether or not the threat is valid does not matter; when the perception or bias is real, then the concern is real and must be addressed professionally, tactfully, respectfully, thoroughly and convincingly.

Some of the stated opposition and concerns are indefensible; "I am against mining – period;" "not in my backyard;" "I do not care that you have an air permit, the state permitting system is faulty;" etc. These types of comments may be impossible to address.

Many concerns are legitimate and must be addressed directly. Identify the concerns from the ordinance, neighbors, decision shapers, decision makers, the local press, letters, emails, blogs and the experience of the technical team. Concerns also can be identified through door-to-door visit to all adjacent neighbors, and possibly beyond adjoining properties, of a proposed project by a representative of the mine operator to describe the project, field questions and address concerns. All the concerns that can be anticipated should be addressed in the early stage of the application process, not after they are voiced at a public hearing; although sometimes there may be unanticipated concerns that could be raised at the public hearing that may require some follow-up. In general, the legitimate concerns that will need to be addressed fall into one of the following categories:

- Economic impact – to local economy, property values, etc.
- Social impact – philanthropy, noise, traffic, truck track-out, lighting, etc.
- Community safety and health
- General environmental and geological – varies by area but may include visual impacts, loss of trees, loss of hills, other physical changes to landscape, wildlife impacts, blasting and underground mining resulting in earth quakes and collapse of area, etc.
- Blasting and vibrations and impact on structures and wells
- Air quality – dust, crystalline silica, asbestos, radon, etc.
- Surface water quality
- Groundwater quality
- Groundwater quantity
- Reclamation

When the concerns can be anticipated, they should be addressed in the permit application process rather than waiting to confirm whether or not they will be raised during the public hearing process.

For existing operations that anticipate future permit renewal or modification requests, perhaps the most important thing that can be done is to honor any agreements reached and comply with the requirements of existing land use and other environmental permits. At the time of permit application, expound on your success at honoring past agreements and complying with permits. Expect and be prepared for any permit or environmental non-compliance or enforcement issues to be raised in the process and be prepared to describe the issue and what was/is being done to address the issue. Beyond complying with all required permit conditions, promoting good community relations and generating good will with the community can go a long way in facilitating permit renewals and mine modification requests.

4.2.5 Mining and the Community

In the process of mining, a natural resource is extracted from a community with the potential for adverse impacts to the community and the environment. A mine is commonly regarded as an unwelcome neighbor in a community. As a good corporate citizen and member of the community, the mining company has a responsibility to make a return to the community in the way that it operates and interacts in the community. The typically poor public image of mining can be partially counteracted by the mining company or mine operator finding ways to give back to the community through support of community events and volunteering for and even spearheading community improvement projects

4.3 Land Management and Quality

One of the most important assets of an aggregates mine is the land associated with the operation. The aggregates industry recognizes the value that land represents and the importance of being responsible stewards of that land. The following sections of this chapter provide information on land use issues affecting the aggregates industry and some of the approaches used to address the issues and concerns.

4.3.1 Land Management

Historically, maintaining regulatory compliance and operating within the conditions of applicable environmental permits was viewed by many as all that was needed, but the expectations of governmental agencies, landowners, community leaders, neighbors and the general public have moved beyond this basic compliance expectation. The environment that the aggregates industry operates in today demands regulatory compliance, but also expects the aggregates operation to be an integral part of the community, be compatible with the surrounding land use and to pay attention to the interests of the neighbors, community and other stakeholders potentially impacted by the operation. Some of the considerations the aggregates industry must address to be successful in gaining approval for the use of land for aggregates mining and production, whether a new operation or an expansion to an existing operation, include the following:

- Ensuring that the planned use for the property is compatible with both current and any planned uses of land surrounding the operation. This includes ensuring that the property is either currently zoned for the intended use or that obtaining the proper zoning is feasible.

- Determining whether the land includes or is near sensitive environmental receptors or ecosystems such as listed threatened or endangered species, wetlands or jurisdictional waters, cultural or historic resources or others so the operation can be designed at the front-end to either avoid impacting the areas or obtain permits or authorization needed to address anticipated impacts.

- Determining who the stakeholders are in the permitting process and engaging in open dialogue regarding their concerns and expectations in advance of the project evaluation and decision making process. Common stakeholders will be neighbors, community leaders and regulatory agency personnel. The extent to which aggregates operators understand and address the concerns of these major stakeholders prior to the decision making process can be a significant factor in the success of the permitting and zoning process.

- Developing a comprehensive mining plan and reclamation plan for the facility that incorporates the issues and concerns addressed in the permit application as summarized in the section on Mine Permitting Concerns.

4.3.2 Layout of Operation

The physical location of the mining operation, processing plant, stockpile area, haul roads and customer loading areas should be developed with the goal of minimizing any impact to sensitive environmental receptors as well as taking into account concerns and issues of stakeholders such as neighbors and the community. Some considerations that aggregates operators must evaluate when designing the mine plan and reaching decision on the physical layout of the site to reduce these impacts include the following:

- Proximity of the processing equipment, load out areas and haul roads to the property boundary and the location of neighbors.

- Distance between the sources and the receptors, barriers such as tree lines, physical features such as hills or differences in elevations, location of haul roads, entrances and exits.

- Drainage patterns and locations of operations in relation to water features such as wetlands and jurisdictional streams.

- Locations of water retention ponds, overburden storage areas, etc. and how that affects both future operations but also the reclamation and end-use of the property. Overburden storage areas also can be a factor with the community from an aesthetics perspective.

- Locations of any sensitive environmental receptors such as listed species, cultural or historic resources, etc. and how the mine site will be developed to either avoid impacts or to comply with permits and authorizations granted to affect those areas.

4.3.3 Appearance

The mine property appearance or visual impact of a proposed operation, is one of the first concerns of the residents of a community. The aggregates industry has long recognized the importance of beautification and site appearance with regard to quarry development. The NSSGA, which represents companies throughout the industry, annually recognizes and awards aggregates producers that make constructive and positive efforts to enhance the appearance of their property. Attention is given to these efforts through publicity within the aggregates industry and the local communities. Some of the benefits of improving site appearances include support from the local community, better impressions of the community, inspectors and regulatory agencies; and the boosting of company morale because employees feel more pride in their company.

Appearance greatly influences the first impression and reputation of an aggregates operation. Mining and the processing plant should be designed to be inconspicuous to the public. A low profile can be accomplished by proper design of the quarry and processing plant. Much of the operation's area can be hidden by trees on the site or by earthen berms. If the entrance area and surrounding perimeters of a pit or quarry are aesthetically pleasing, positive impressions are more likely to be established in the community. The self pride and worth of a company are greatly enhanced by maintaining a positive community image. A pleasing site appearance also helps promote the acceptance of new sites in the permitting process. Figure 4.1 (see color section) shows an example of an aggregates operation that has been recognized by the NSSGA and highlights participation in a voluntary environmental program.

The entrance to a pit or quarry should be designed to provide an attractive image to the passerby and identify the name of the operator. Another example of attractive entrance landscaping is presented in Figure 4.2 (see color section). Entrances can be beautified with flowers, shrubs and grass, as well as attractive wrought iron gates, wooden gates, stone walls and attractive signs. Many landscape departments at universities have general landscape plans available for individual complex entrances and adjacent areas. The plant buildings, switch houses and office buildings located within the quarry site should be freshly painted and maintained.

MSHA regulations and most mine permits require that access to the property be restricted. This is often accomplished through the installation and maintenance of berms around the perimeter of aggregates mining sites. These berms provide several benefits including:

- Being visually appealing to the community and people who drive past the operations. In many cases, people go by quarries every day and are not aware that a quarry exists.

- Providing a shield between the operation and the public that reduces noise and ambient light associated with nighttime operation.

- Providing a safety barrier to reduce the chance of someone wandering unknowingly onto a mining operation.

- Providing a habitat for the protection of wildlife.

4.3.4 Reclamation

Mining is a temporary land use. Before an existing property is mined, the end-use plan must be developed. Mine reclamation planning is done early in the mine planning process to minimize and mitigate the environmental effects of operation of the mine and develop a final land use plan that may incorporate agricultural, recreation and wildlife use. Reclamation is best conducted as an ongoing process when possible with the reclamation phased as mining progresses to:

- Minimize movement of soil from earlier phases in later phases for filling and top soil;
- Minimize the amount of surface that is open at any one time; and
- Allow communities to visualize what the reclaimed mine will look like when completed.

Mines that have been operating for many decades often have limited reclamation opportunities or requirements and the ability to retroactively reclaim the mine is limited, so these older operations often are used for recreational purposes, such as lake development, after mining is completed. However, newer operations often are designed and permitted with a specific post mining land use in mind.

In areas where reclamation plans are required as part of the permitting and land use authorization process, aggregates operators must comply with the procedures and activities outlined in the plan, as they are essentially part of the authorization to operate. The specific actions an operator takes in reclaiming the site are dependent on the end-use plan for the site and the requirements in any applicable reclamation plan and mine permit.

The post mining land use of an aggregates mine property often provides a substantial value to the aggregates operator and significant social value to the community associated with the continued use of the property. Some post-mining uses of aggregates mine properties include the following:

- Highly valued residential lake property
- Commercial or industrial development
- Amusement parks
- Public and private recreation, including swimming, hiking, sports complexes, etc.
- Golf courses and parks
- Wetland and endangered species banks; wildlife refuge and waterfowl habitats
- Water reservoirs
- Agricultural pasture and cropland
- Stormwater retention basins

In summary, aggregates producers have become increasingly aware that the land they use for mining and processing of aggregates has long-term value to the company and the community. The proper management of this land is critical to ensure that it is mined in a manner that supports its intended end use.

For underground mines, reclamation is not as significantly challenging. Underground mines are used for commercial purposes, such as cold storage, may be used for scientific study or preserved for bat habitat. Mines also may be considered for filling with construction debris, water treatment sludge, coal ash or other low hazard materials. Underground mine reclamation options also will depend in large part on the location of the groundwater table as potential for re-use will depend in large part on the energy required to maintain dewatering.

4.4 Surface Water Quality

Surface water quality can be impacted by a wide variety of construction and mining operations, as well as many other types of activities that discharge materials to water bodies either directly or indirectly. The federal Clean Water Act (CWA) and other pieces of environmental legislation protect surface water through the regulation of point sources and stormwater under the federal National Pollutant Discharge Elimination System (NPDES) permit program, as well as other programs established to address various water management issues.

4.4.1 Stormwater Management and Sediment Control

As aggregates mining sites are developed, the native vegetation in the mining area is cleared and the overburden is removed to gain access to the sand and gravel or bedrock reserves. This creates a potential for the soil to be eroded during storm events and for sediment to be discharged via the stormwater runoff. Aggregates mining operations that discharge stormwater from the operation are required to obtain a stormwater or combined process/stormwater permit for these discharges. In some cases, the stormwater drains to the pit and if the pit has sufficient capacity, the stormwater may not be released from the site. In either case, aggregates operations implement various sediment control measures as a means of minimizing the amount of soil that is lost due to erosion from storm events.

Erosion is a natural process by which soil and rock particles are loosened from their original locations and then transported to new locations on the earth's surface. Erosion by the action of water, wind or ice has been responsible for many of the earth's irregularities and has provided material deposited over vast areas. The erosive process which normally proceeds at a slow but relatively constant rate is greatly accelerated when surface mining activities remove protective vegetative cover, expose underlying soil and weathered rock and increase slopes and thus the rate of surface water movement. For these reasons and for the protection of surrounding areas, it is important that erosion control plans be developed in advance of such disturbance.

The erosion process begins when water, falling as raindrops, begins to flow on a soil surface. Figure 4.3 illustrates four types of soil erosion which can occur on exposed terrain: *splash, sheet, rill and gully,* and *stream and channel.* Splash erosion results when the force of raindrops falling on bare or sparsely vegetated soil detaches soil particles. Sheet erosion occurs when these soil particles are easily transported in a thin layer or sheet by flowing water. If sheet runoff is allowed to concentrate and gain velocity, it cuts rills and gullies as more soil particles are detached. As the erosive force of flowing water increases with slope length and gradient, gullies become deep channels and gorges. The greater the distance and slope, the more difficult it is to control. Erosion damage also becomes greater with increasing volume and velocity of runoff.

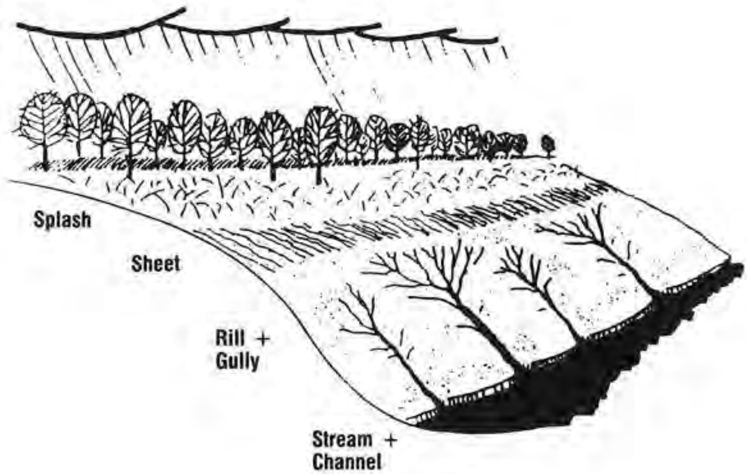


Figure 4.3 Four types of soil erosion on an exposed slope.

Damage from sedimentation caused by erosion is undesirable both economically and environmentally. Sediment deposition destroys fish spawning beds, reduces the useful storage volume in reservoirs, clogs streams and may carry toxic chemicals. Suspended sediment requires costly filtration if the water is used for municipal water supplies. Suspended sediment reduces in-stream photosynthesis and alters a stream's ecology. Many environmental impacts from sediment are cumulative, and the ultimate results and costs may not be evident for years. The consequences of off-site sedimentation can be severe and should not be considered a problem only for those immediately affected. On-site erosion and sedimentation cause costly site damage and can interfere with production operations. Maintenance of erosion control facilities is essential.

Erosion and Sediment Control

The following principles of erosion and sediment control are effective if properly applied:[1]

1. **Fit the mine development to existing site conditions.** To the maximum extent possible, be sure that all roadways, drainage ditches and work areas fit the land contours without requirement for needless excavation. Level, well-drained areas offer few restrictions. Any modification of a site's natural drainage features or of its topography, requires protection from erosion and sedimentation.

2. **Minimize the extent and duration of exposure.** Proper scheduling of excavation activities can be effective in minimizing the probability of erosion. Such activities should be planned to minimize the areas of disturbance and duration of exposure. When scheduling, consider the season of the year and the weather forecasts. Stabilize all disturbed areas as quickly as possible.

3. **Protect areas to be disturbed from stormwater runoff.** Use dikes, diversions and waterways to intercept runoff and divert it away from cut-and-fill slopes or other disturbed areas. To

reduce on-site erosion, install these measures before clearing and excavation operations begin. Figure 4.4 shows a stormwater diversion channel adjacent to a fill slope to protect against erosion.

Figure 4.4 A typical stormwater diversion channel.

4. **Stabilize disturbed areas.** Removing the vegetative cover increases an area's susceptibility to erosion. Apply stabilizing measures as soon as possible after the land is disturbed. Plan and implement temporary or permanent vegetation, mulches, wheat straw or other protective practices to correspond with mining activities. Protect channels from erosive forces by using protective linings and an appropriate channel design (i.e., sufficient cross-sectional area and minimum acceptable slope). Consider possible future repairs and maintenance of these erosion control devices during their design.

5. **Keep runoff velocities low.** Clearing existing vegetation reduces the surface roughness and infiltration rate and thereby increases runoff velocities and volumes. Use measures to break the slopes, reducing the problems associated with concentrated flow volumes and runoff velocities. Practical ways to reduce velocities include diverting stormwater runoff away from steep slopes to stabilized outlets, preserving natural vegetation where possible and mulching and vegetating exposed areas immediately after disturbance. Stormwater management design criteria vary widely between states and local municipalities. Design guidelines should be incorporated into the erosion control plan.

6. **Retain sediment on the site.** Even with careful planning some erosion is unavoidable. The resulting sediment must be trapped on the site. Plan the location where sediment deposition will occur and maintain access for cleanout. Protect low points below disturbed areas by building barriers, such as silt fences and dikes, to reduce sediment loss. Whenever possible, plan and construct sediment traps and basins before land-disturbing activities.

7. **Inspect and maintain control measures.** Inspection and maintenance is vital to the performance of erosion and sedimentation control measures. If not properly maintained, some erosion control practices cause more damage than they prevent. Always evaluate the consequences of a control measure when considering which one to use. Failure of an erosion control device can be hazardous or damaging to both people and property. For example, failure of a large sediment basin can have disastrous results. Low points in dikes can cause major erosion gullies to form on a fill slope. All erosion control facilities should be inspected and maintained to assure that problems are corrected as soon as they develop.

4.4.2 Surface Water Permitting

The applicable regulatory requirements can be driven by many factors, including the analysis of specifically defined terms regarding source of the discharge and its constituents, the manner in which it is discharged and the type of water body to which the discharge is directed. Section 402 of the federal CWA establishes the NPDES permit program, which regulates the discharge of pollutants from a "point source" into "waters of the United States." An NPDES permit sets limits on pollutants that may be discharged, and establishes monitoring and reporting requirements for such discharges.[1] The individual states also have established programs to regulate pollutant discharges. In most cases, the states have sought and received federal delegation of authority to implement the federal program in conjunction with their state program.[2] Compliance with the state program requirements generally satisfies federal program requirements in delegated states. The following discussion of regulatory requirements will focus on the federal program. States are allowed to impose more stringent standards and the reader is advised to carefully review state regulations for the requirements applicable to their operations.

To determine whether your discharge requires an NPDES permit, it is important to understand what constitutes a "pollutant" and a "point source." Under the CWA, the term "pollutant" is defined broadly to include "dredged spoil, solid waste, incinerator residue, sewage, garbage, sewage sludge, munitions, chemical wastes, biological materials, radioactive materials, heat, wrecked or discarded equipment, rock, sand, cellar dirt and industrial, municipal and agricultural waste discharged into water."[3] A "point source" is defined as "any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, [or] conduit … from which pollutants are or may be discharged."[4] The term "point source" has been construed broadly.[5]

In addition to what is generally described as end-of-pipe discharges regulated under Section 402, Section 404 of the CWA establishes a specific program to regulate the discharge of dredged or fill material into waters of the United States, including discharges to wetlands. In the context of activities in wetlands, the excavation or dredging of wetlands may constitute discharges regulated by the CWA. Dredge material is defined to include "material that is excavated or dredged from waters of the United States."[6] Fill material is defined to include material placed in waters of the United States where the material has the effect of (1) replacing any portion of a water of the United States with dry land or (2) changing the bottom elevation of any portion of a water of the United States.[7] Examples of fill material include rock, sand, soil, clay, plastics, construction debris, wood chips, overburden from mining or other excavation activities and materials used to create any structure or infrastructure in the waters of the United States.[8] Fill material does not include trash or garbage.[9]

Under both Sections 402 and 404, a regulated discharge is one that is directed to certain defined "waters of the United States." The discharge of end-of-pipe wastewater to regulated bodies of water that is subject to regulation is often quite obvious. The discharge of dredged or fill material in wetlands may sometimes be more challenging to evaluate. In addition, making a correct determination of when such activities cause discharges to "waters of the United States" is critical. The complexity of issues related to a determination of whether a discharge involves regulated receiving waters is reflected in the substantial debate among government agencies; and among those agencies, regulated industry members and the input of the courts, including the U. S. Supreme Court.

In 2011, the U. S. Environmental Protection Agency and the U. S. Army Corps of Engineers, following recent federal court determinations, developed the most recent version of draft guidance documents for determining whether a waterway, water body or wetland is protected by the CWA.[10] In this guidance, there are three categories of waters: (1) waters that are protected by the CWA; (2) waters that are protected by the CWA if they have a "significant nexus" to navigable or interstate water; and (3) areas that are not protected by the CWA. The agencies published the following summary describing which waters are within the CWA jurisdiction:

The agencies determined the following waters are protected by the CWA:

- Traditional navigable waters
- Interstate waters
- Wetlands adjacent to either traditional navigable waters or interstate waters
- Non-navigable tributaries to traditional navigable waters that contain water at least seasonally
- Wetlands that directly abut relatively permanent waters

In addition, the agencies determined that the CWA would protect the following waters, if they have a "significant nexus" to a navigable water or interstate water:

- Tributaries to navigable waters or interstate waters
- Wetlands adjacent to jurisdictional tributaries to navigable waters or interstate waters and
- Waters that fall under the "other waters" category of the CWA

Finally, the agencies acknowledged that the CWA does not regulate the following:

- Wet areas that are not tributaries or open waters and do not meet the agencies' regulatory definition of "wetlands"
- Waters excluded from coverage under the CWA
- Artificially irrigated areas that would revert to upland should irrigation cease
- Artificial lakes or ponds created by excavating and/or diking dry land and used exclusively for stock watering, irrigation, settling basins or rice growing
- Artificial reflecting pools or swimming pools created by excavating and/or diking dry land
- Small ornamental waters created for primarily aesthetic reasons
- Water-filled depressions created incidental to construction activity
- Groundwater drained through subsurface drainage systems
- Erosional features (gullies and rills) and swales and ditches that are not tributaries or wetlands[11]

Various mining activities may result in a regulated discharge of pollutants from a point source into waters of the United States or the discharge of fill or dredge into such waters. For example, the construction of impoundments in wetlands likely would be regulated under Section 404 of the CWA and a discharge from such impoundments into other waters likely would be regulated under Section 402.[12] All activities that are planned to occur in the vicinity of wetlands or water-courses and all discharges to such areas should be carefully reviewed in advance to identify applicable permitting requirements. The preparation of CWA permit applications, and the corresponding review and approval process can be lengthy. Determining whether CWA jurisdiction extends to your activities should be a first priority in your regulatory compliance project checklist.

4.4.3 Process Water Management

One of the most challenging parts of a plant design effort is the handling of the waste water and its products that are discharged from the processing streams of a normal plant operation. If the plant process operates dry, some of the final clean stone products may require rinsing to meet specifications. In addition, the demand for manufactured sand from stone screenings is increasing and this generally requires the use of water separation of the excess fine material. Handling of the process water is a relatively straightforward task; however, the recovery and disposal of the fines are difficult and can be handled in one of the following ways:

- **Closed Circuit Settling Ponds:** The traditional method for the disposal of fines is to discharge the process water into *closed circuit settling ponds* for decantation. The use of this approach is diminishing. A number of ponds must be constructed and large areas are required. In many applications, the material in the ponds (tailings) must be routinely excavated. The removed fines are hauled to the reclamation area which adds costs to the operation. The most cost-effective way of disposal is the construction of permanent disposal areas where fines are pumped directly from the wash process. However; these types of impoundments may need to be approved by state authorities, possibly subject to inspection by MSHA and the water return system monitored constantly.

- **Concrete Containment Cells:** The use of above-ground *concrete containment cells* provides a method of settling out the coarser fractions of the wash water that permits access with front-end loaders after water decantation. The use of containment cells enables the material to be handled by truck in a more cost-effective way. The overflow water from these basins is collected in ponds to undergo final sedimentation settling.

- **Clarifiers:** Clarifiers are a means of eliminating the use of ponds and their associated cleaning expenses.
  - *A plate clarifier* is a system of closely spaced inclined plates at a one-to-one slope that provides a multiple passage for water and fines. A plate clarifier permits an installation in one-tenth the space required for circular clarifiers.
  - In a *circular clarifier*, sometimes called a thickener, settled particles are moved to the tank center by radial rakes for discharge. These units are constructed of steel or concrete and normally have a large diameter (80 to 150 feet) to provide a quiet pool for particle settling.
  - The rake clarifier is a rectangular tank with a slow-moving drag flight conveyor which removes settled solids up and over a discharge ramp onto a dewatering pad or basin. When proper flocculants are added, this unit has a discharge with a moisture level that enables loader handling fairly quickly.

Many plant process water systems are essentially *closed circuit systems* with no water discharge leaving the property. Makeup water is provided by mine water or groundwater wells. Belt presses and vacuum filter systems are available to remove residual moisture from the effluent of clarifiers; however, these systems are quite expensive and are not commonly utilized at aggregates processing operations unless the product can be sold for commercial use.

The use of flocculants in waste water handling is becoming more prevalent. Flocculants cause the rapid settling of coagulated fines and enable the immediate reuse of the clean water in the plant process. The more rapid recycling of the waste water reduces the volume of water handled and simplifies the required plant makeup water systems. The use of flocculants does not, however, provide a solution for the handling of the effluent and suspended fines as previously discussed.

Providing for facility drainage and stormwater control is essential in the aggregates processing facility design due to the stringent controls imposed by regulators on water discharges. The plant drainage design must accommodate process plant cleanup water from the plant maintenance systems, cooling water from the crushing systems, building drainage and runoff from dust control and irrigation systems. Drainage structure must be established that permit proper water flows in and around the buildings and stockpiles. Water courses, such as ditches and storm sewers, must be provided which do not interfere with plant operating or maintenance procedures. Most operating permits require sufficient water storage capacity to contain the flow from unusually severe rainfall conditions and sufficient time for settlement of suspended solids. Stormwater may be stored in ponds and released to the normal water courses when the water quality requirements of the plant discharge permits are satisfied.

4.4.4 NPDES Permits - Process Discharges and Permit Options

An NDPES permit generally would be required for the discharge of process wastewater to regulated water bodies. "Process Wastewater" includes "any water which, during manufacturing or processing, comes into direct contact with or results from the production or use of any raw material, intermediate product, finished product, byproduct or waste product."[13] If a company will be discharging process water, they should to review EPA and state-specific permitting requirements before initiating such a discharge.[14]

The two fundamental types of NPDES permits are individual permits and general permits. An individual permit is prepared by the agency based on a review of detailed application information for a specific facility and discharge. Such a permit is issued to a facility for a specific time period (not to exceed five years) and the facility must reapply for renewal of the permit prior to the expiration date.

An individual permit application is subject to a preliminary review for completeness and accuracy. Additional information may be requested from the applicant. When the application is complete, the agency will develop the draft permit, including technology-based effluent limits and effluent limits that satisfy federal and state water quality standards (i.e., water quality-based effluent limits). The agency also will develop monitoring and reporting requirements, facility-specific special conditions and include standard conditions that are the same for all permits. Once complete, the agency will publish public notice of the proposed permit decision and provide an opportunity for public comment on the draft permit. Based on the comments, the agency may develop and issue a final permit in original form or modified by the agency to address public comments deemed valid.

A general permit, in contrast, is a model document of terms and conditions that apply to discharges from categories of similar facilities or activities. General permits may cover categories of point sources having common elements, such as:

- Stormwater point sources
- Facilities that involve the same or substantially similar types of operations
- Facilities that discharge the same types of wastes or engage in the same types of sludge use or disposal practices
- Facilities that require the same effluent limitations, operating conditions or standards for sewage sludge use or disposal
- Facilities that require the same or similar monitoring
- Facilities that, in the opinion of the agency, are more appropriately controlled under a general permit rather than under individual permits[15]

General permits may be limited to use in a specific geographical area, such as a city, county or state political boundaries, designated planning area, sewer district, state highway system or urbanized area. It is important to ensure that your facility and activities meet all qualifications for use of a general permit. In addition, the qualification process may vary for different general permits. Some require an application and agency approval. Others only require notice of registration under the general permit and commitment to comply with the permit requirements. A third category is general permits that authorize defined activities to all qualified users without the need to file an application or a notice with the agency and provides the legal authority to discharge in accordance with their terms and conditions.

All NPDES permits should, at a minimum, consist of five general sections:

1. Cover Page—Typically containing the name and location of the permittee, a statement authorizing the discharge and the specific locations for which a discharge is authorized.

2. Effluent Limits—May include numeric limits for permissible constituents, volume restrictions or other limitations.

3. Monitoring and Reporting Requirements—May require periodic testing of discharge characteristics and reporting of test results, violations of permit restrictions or treatment system irregularities.

4. Special Conditions—Conditions developed to supplement effluent limit numeric guidelines. For examples, imposing obligations to implement best management practices (BMPs), additional monitoring activities, ambient stream surveys or toxicity reduction evaluations.

5. Standard Conditions—Conditions that apply to all NPDES permits and delineate the legal, administrative and procedural requirements of the permit.[16]

4.4.5 NPDES Permitting for Stormwater Discharges

Generally, stormwater runoff is rain water or snowmelt that flows over land or impervious surfaces and is not absorbed into the ground. As the water travels over these surfaces, it may accumulate pollutants that could adversely affect water quality if discharged. NPDES permits are required for certain stormwater discharges, if the stormwater leaves a site through a "point source" (as defined in section 4.4.1) and reaches surface waters either directly or through a storm drain.

The NPDES Stormwater Program covers three categories of stormwater discharges:

- Municipal Separate Storm Sewer Systems (MS4s)
- Construction Activities
- Industrial Activities[17]

Most states are authorized to implement the Stormwater NPDES permitting program.[18] However, EPA remains the permitting authority in a few states and territories.

An MS4 permit is required for a system of conveyances that is: "(1) Owned by a state, city, town, village or other public entity that discharges to waters of the U.S.; (2) Designed or used to collect or convey stormwater; (3) Not a combined sewer; and (4) Not part of a Publicly Owned Treatment Works (sewage treatment plant)".[19]

EPA regulations identify 11 categories of stormwater discharges that must be covered under an NPDES permit. One category (Category Ten) requires regulation of stormwater discharges from construction sites. Given its importance, the EPA has created a separate NPDES permit for construction sites engaged in clearing, grading and excavating activities that disturb one acre or more (or smaller sites in a larger common plan).[20] In areas where EPA is the permitting authority (i.e., the state has not been delegated permitting authority), operators must meet the requirements of the EPA Construction General Permit (CGP). (Available at cfpub.epa.gov/npdes/stormwater/cgp.cfm.) Other categories of industrial activities of potential interest to mining or aggregates operations include the following:

- Category One (i): Facilities subject to the federal stormwater effluent discharge standards contained in 40 C.F.R. Parts 405-471, including mineral mining and processing, certain coal mining and ore mining and dressing.[21]
- Category Two (ii): Certain "heavy" manufacturing (for example, steel mills, foundries and cement kiln operations).[22]
- Category Three (iii): Coal and mineral mining, and oil and gas exploration and processing facilities.[23]

Stormwater Individual Permits vs. General Permits

As discussed above, the NPDES Stormwater Program generally regulates stormwater discharges from three potential sources: municipal separate storm sewer systems (MS4s), construction activities and industrial activities. The EPA has authorized 46 states to issue NPDES permits.[24] In addition, many states have enacted their own stormwater management laws and regulations, which may include additional, more stringent requirements. In assessing whether your planned activities need a stormwater permit, you should confirm whether there are additional permitting requirements at the state level.

Stormwater general permits cover categories of activity that have similar operations, discharge similar types of wastes, require the same effluent limits and require similar monitoring. Generally, to be covered by a general permit, an applicant must submit a Notice of Intent.[25] In several states, however, by following the requirements of the general permit for a category of activity, the applicant is automatically covered by the permit and no application is required. General permits do not require public comment for each activity or applicant. However, the public may comment on the general permits terms when it is being developed or when it is being renewed.

If a general permit does not authorize certain planned activities, an applicant may elect to apply for an individual permit. Individual permits are specific to a particular activity and location. Because individual permits are tailored to the activity and the location, each permit is unique and contains specific requirements. Public notice and comment is required before an individual permit may be issued.

EPA has issued a Multi-Sector General Permit (MSGP) that addresses stormwater discharges from 29 sectors of industrial activity.[26] The 29 sectors are defined by either the facility's Standard Industrial Classification (SIC) code or the facility's industrial activities. The North American Industry Classification System (NAICS) eventually will replace the SIC system. Industry sectors of potential interest to mining or aggregates operations include:

- Metal mining (ore mining and dressing) facilities as defined by Standard Industrial Classification (SIC) Major Group 10
- Glass, clay, cement, concrete and gypsum product manufacturing facilities as described by Standard Industrial Classification (SIC) Major Group 32
- Coal mines and coal mining-related facilities as defined by Standard Industrial Classification (SIC) Major Group Code 12
- Discharges that have been exposed to significant materials from active and inactive mineral mining and processing facilities as defined by Standard Industrial Classification (SIC) Major Group 14[27]

Construction Stormwater Discharge Permits

Under federal standards, stormwater discharges associated with construction activities that disturb one or more acres (or smaller sites that are part of a larger common plan of development or sale) are required to obtain an NPDES permit, which is administered either by the state (if it has been authorized) or EPA.

Most construction stormwater discharges are addressed by the Construction General Permit (CGP) when EPA is the permitting authority.[28] To obtain coverage under the CGP, an applicant must submit a Notice of Intent certifying that it meets the permit's eligibility conditions and will comply with the permit requirements, including its effluent limitations.[29] Use of the CGP also will require the facility to develop a Stormwater Pollution Prevention Plan.

On April 25, 2011, EPA published notice of a proposed draft of its new CGP.[30] The new CGP proposes to modify the existing permit to implement the Effluent Limitations Guidelines and New Source Performance Standards for Construction and Development point sources (the "C&D rule"). "The C&D rule requires construction site operators to meet restrictions on erosion and sediment control, pollution prevention and stabilization."[31]

Mining operations often perform activities that are regulated as construction activities under the stormwater permit program. Thus, each such operation should assess whether a general or individual permit would be required before discharging stormwater from a point source.

4.4.6 Wetlands

Management of wetlands resources has become the focus of increased national attention in recent years. Public awareness has greatly increased concerning the ecological significance of wetlands and the large scale at which they have been destroyed in the United States. Wetlands are found throughout the country and generally include swamps, marshes, bogs and similar areas. Wetlands are technically defined under federal law as[52] *"areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support and that under normal circumstances do support, a prevalence of vegetation typically adapted to life in saturated soil conditions."* The definition of what constitutes a "wetland" may vary under respective state laws.

Surprisingly, however, land need not look wet to fall under the definition of a wetland. In fact, many wetlands do not contain visible surface water, but the soils are merely saturated just beneath the ground surface over a portion of each year.

In 1995 the National Research Council of the National Academy of Science developed the following reference definition of wetlands:

> *A wetland is an ecosystem that depends on constant or recurrent, shallow inundation or saturation at or near the surface of the substrate. The minimum essential characteristics of a wetland are recurrent, sustained inundation or saturation at or near the surface and the presence of physical, chemical and biological features reflective of recurrent, sustained inundation or saturation. Common diagnostic features of wetlands are hydric soils and hydrophytic vegetation. These features will be present except where specific physicochemical, biotic or anthropogenic factors have removed them or prevented their development.*

> Until an agreement is reached by Congress on a universally accepted definition of wetlands and legislation is passed to enact that language into law, the regulated community must continue to rely on the interpretations of existing wetlands reference documents such as the 1995 National Research Council's reference definition cited above and the 1987 and 1989 Corps of Engineers' *Federal Manual for Identifying and Delineating Jurisdictional Wetlands*. The Wetlands definition given by USACE is presented in *The Aggregates Handbook*. Each of the documents cited above define wetlands based on differing characteristics and combinations of hydrology, hydric soils and hydrophytic vegetation.

4.4.6.1 Role and Significance of Wetlands

According to the National Wetlands Policy Forum Report[53]:

> "The nation is now coming to realize that wetlands have great value in their natural state. Their biological productivity can exceed that of the best agricultural lands. A broad array of wildlife, fisheries and other aquatic resources depends on them. Wetlands sustain nearly one-third of the nation's endangered and threatened species. They provide

> breeding and wintering grounds for millions of waterfowl and shorebirds every year. Coastal wetlands provide nursery and spawning grounds for 60 percent to 90 percent of U.S. commercial fish catches.
>
> Wetlands also play key roles in regional hydrological cycles—lessening flood damage, reducing erosion, recharging groundwater, filtering sediment and abating pollution. Within a landscape, they are linked to both upstream and downstream ecosystems and their functional values may extend well beyond the boundaries of the wetlands themselves. At an extreme, as in the case of some migratory birds, habitat functions can extend even to other continents.
>
> At the same time, property containing wetlands is valuable for other purposes as well. Facilities such as ports and marinas need to be adjacent to water. In some metropolitan areas, the only large, flat, open, centrally located parcels of available land contain wetlands, making them prime sites for shopping centers, industrial parks, airports, parks, highway and utility crossings and other large developments. Wetlands may overlie important oil, gas and other mineral deposits or support valuable stands of timber. In agricultural areas, they may provide the only land that individual farmers can readily make use of to expand their cropped acreage."

The Congress considers 90 million acres or 5 percent of the contiguous United States and 200 million acres in Alaska or 60 percent of that state's land area[54] as wetlands. Ninety-five percent of wetlands in the United States are inland or freshwater wetlands.

The most recent estimates of the rate of wetlands loss are based on data collected during the 1950s and 1960s. Those studies concluded that roughly 215 million acres of wetlands existed at the time of the nation's settlement. By the mid-1970s, 99 million acres remained in the lower 48 states-a loss of 54 percent. From the mid-1950s to the mid-1970s, an average of 458,000 acres were lost per year. The agricultural sector accounted for 87 percent of this loss, urban development for 8 percent and other development, such as timber harvesting, water management and infrastructure projects, for the remaining 5 percent.

A number of federal laws are presently in effect that protect wetlands resources.[55] The Fish and Wildlife Resource Act,[56] the Fish and Wildlife Coordination Act,[57] the Migratory Bird Treaty Act,[58] and the Endangered Species Act[59] protect fish and wildlife. The Coastal Zone Management Act[60] and the Coastal Barriers Resource Act protect coastal areas.[61] In addition, the Emergency Wetlands Resources Act[62] established a National Wetlands Priority Conservation Plan for wetlands protection and acquisition.

4.4.6.2 Identification and Delineation

The following governmental agencies are responsible for identifying and delineating (i.e., defining) wetlands:

- U. S. Environmental Protection Agency (EPA)
- U. S. Army Corps of Engineers (USACE)
- Department of the Interior's Fish and Wildlife Service (FWS)
- Department of Agriculture's National Resources Conservation Service (NRCS)

The EPA and USACE jointly administer the Clean Water Act's Section 404 program. Under this program, anyone seeking to engage in any activity that would result in the deposit of dredged or fill material in any water of the U.S. including wetlands must first obtain a permit from the USACE. In many states, the process of obtaining a Section 404 permit is through a joint application process in which both the USACE and a state agency that is charged with protection and regulation of the state's water resources, review the application and the USACE cannot grant the Section 404 permit with the state agency's certification (a/k/a "water quality certification"). The permit process may involve a *compensatory mitigation plan* in which the landowner agrees to create or restore or purchase mitigation credits in a wetland bank, a comparable amount of wetlands elsewhere. In addition, many states now have developed their own wetlands protection regulations and permitting and mitigation requirements that may be more restrictive than federal regulations.

A manual[52] prepared by four federal agencies (the Corp of Engineers, the Environmental Protection Agency, the Fish and Wildlife Service and the Soil Conservation Service) to help locate wetlands establishes three wetland indicators:

- Wetland vegetation
- Wetland hydrology
- Wetland soils

These three indicators of wetlands must all be present in one given location before that location is classified as a wetland. This manual is currently the standard by which all federal agencies delineate wetlands.

Frequently, landowners have a qualified, experienced professional determine the extent of wetlands on their property. Detailed procedures used in identifying wetlands are given in the latest edition of the federal manual, *Identifying and Delineating Jurisdictional Wetlands*.[52] This publication is the current standard for delineating wetlands in the United States and contains a great deal of detailed information on classifying wetlands, as well as example data sheets, sample problems and sources of reference material.

Under the federal manual, the following three technical criteria must be satisfied for an area to be classified a wetland: (1) It must have hydrophytic vegetation (plant life growing in water or on a substrate that is at least periodically deficient in oxygen as a result of excessive water content); (2) it must have hydric soils (a soil that is saturated, flooded or ponded long enough during the growing season to develop anaerobic conditions in the upper part); and (3) it must have wetland hydrology (in general terms, permanent or periodic inundation or prolonged soil saturation sufficient to create anaerobic conditions in the soil). If these three technical criteria are met, the area is classified a wetland.

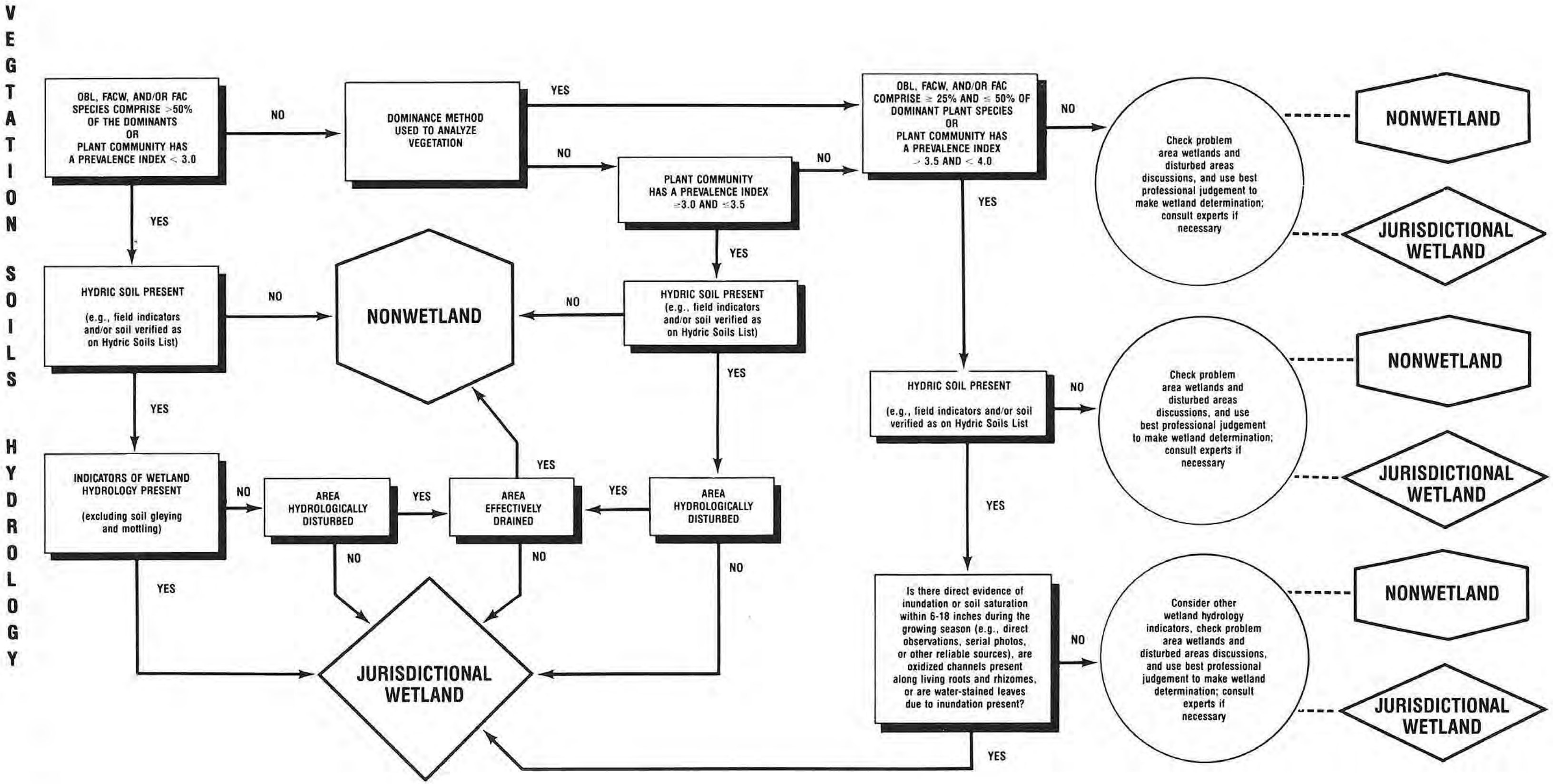


Figure 4.5 Conceptual approaches for making an onsite wetland determination

One of the end products of a wetland delineation survey is usually a map indicating the boundary between wetlands and non-wetlands (uplands). However, it is important to remember that, in reality, on the ground zones of transition or gradation from wetlands to non-wetlands will likely exist, the extent of which are determined by local conditions. Where the jurisdictional line is drawn within that zone is influenced by the professional judgment and experience of the wetlands surveyor and may result in greater or lesser amounts of land being classified as wetlands. It also is important to note that wetland boundaries can change over time due to weather and climatic conditions. Consequently, wetland boundaries that are depicted on documents such as wetland inventory maps, which are often based on historical aerial photographs or other historical information sources, may need to be confirmed by actual onsite (ground truthing) wetland delineation methods.

4.4.6.3 Inadvertently Created Wetlands

It is important to note that man-made alterations to the landscape can inadvertently create a regulated wetland. Activities such as re-grading the surface of a site, placing less permeable fill soils in an area, redirecting drainage ditches, etc., can create conditions that are conducive to the creation of hydric soils, wetland hydrology and growth of hydrophytic vegetation. Once a wetland is established, even if it was created inadvertently, it may become a regulated wetland and thereafter, activities that can alter the wetland, such as dredge or fill activities may require a Section 404 permit before such activities can be conducted.

4.4.6.4 Mining Lands for Establishing Wetland Banks

Wetlands mitigation banking involves restoration, creation or enhancement of wetlands to offset unavoidable wetlands losses elsewhere. Under such a system, the restored, created or enhanced wetlands are considered as *credits* that can be used to offset losses in other areas. Either the USACE or EPA can deny the permit if they decide the activity poses an unacceptable loss of wetlands. Currently no appeals process exists within this permitting system apart from the courts and/or administrative appeals process.

Mitigation is not intended to be a 'one-for-one' acre fair trade. Often, the agency requires a minimum compensation of 1.5 to 2 acres of restored, created or enhanced wetlands for every acre of wetland that is lost. The ratio of compensated wetlands to wetland loss is typically determined by the quality of the wetland loss. For example, compensation for the loss of high quality floodplain forested wetland may require a higher ratio (e.g., 2 to 1) of compensation than a lower quality monotypic cattail marsh. The price per acre for mitigated wetlands in a wetland mitigation bank can be in the range of $25,000 to $50,000 per acre.

It is also important to note that wetland compensatory mitigation is not allowed in every situation in which a Section 404 permit is issued.

4.4.6.5 Regulatory Protection of Wetlands

Section 404 of the Clean Water Act[63] provides significant protection for wetlands resources. Section 404 requires potential dischargers of dredge and fill materials into waters of the United States to secure a permit from the USACE. As noted above, this process is often a joint permit application process with the USACE and a state agency. Guidelines for government personnel to use in determining whether a permit should be granted are given in Section 404(b)(1). Permit applications are often subject to a detailed public interest review process. The U.S. Environmental Protection Agency (EPA) has authority to veto USACE decisions on granting permits. Several categories of activities are excluded from the 404 program, including normal farming, ranching and forestry activities. For these reasons, only about 20 percent of wetlands loss occurs within the Section 404 program.

Section 1221 of the Food Security Act[64] of 1985 (the "Swampbuster" provision) is intended to prevent wetlands loss on agricultural lands. Another program to protect agricultural wetlands requires the Farmer's Home Administration to place easements protecting wetlands on property it acquires in bankruptcy proceedings.

In May of 1977, the White House issued Executive Order 11990, Protection of Wetlands,[65] which directs each federal agency in carrying out its individual responsibilities, to minimize the destruction or degradation of wetlands and to preserve and enhance the natural and beneficial values of wetlands resources.

Several states and local governments also have been active in wetlands protection efforts. State laws differ in their definition of wetlands, whether a state permit is required and how they are monitored. The result is inconsistency regarding wetlands policy among states and between states and the federal government.

It is important to identify any wetlands affected or potentially affected by aggregates operations. Under current requirements, when compensatory mitigation is allowed, for every acre of wetland destroyed at least one and often more than one, new acre of wetland must be created. The creation of new wetlands is an expensive process. As a result, the limits of wetlands must be clearly delineated to prevent inadvertent destruction of existing wetlands—either natural or manmade. The specific wetlands laws ordinances and regulations which apply in each particular state and locality must be carefully identified. At a minimum, Section 404 of the federal Water Pollution Control Act will apply. Wetlands laws and regulations, like other environmental laws and regulations, will continue to evolve and change over an extended period of time. Therefore, individuals involved with aggregates development and renovation must stay current with those changes to avoid excessive mitigation costs or possible penalties.

4.4.6.6 Regulatory Requirements and Permitting for Disturbance of Wetlands

As discussed in section 4.4.2 above, discharges of dredged or fill material to a wetland is regulated by the EPA and USACE through Section 404 of the CWA. Jurisdiction under the CWA is limited to "discharges" as opposed to the withdrawal of material from a wetland. However, the scope of the term "discharge" has been the source of substantial controversy. In the past, the USACE and EPA have attempted to define the term broadly to extend jurisdiction to excavation activities (such as mining) by regulating incidental fallback of material during the dredging or excavation process.[32] The agencies' assertion of jurisdiction over incidental fallback, however, has been invalidated by the decisions of reviewing courts.[33] As of 2008, the term "discharge of dredged material" is defined as "any addition of dredged material into, including redeposit of dredged material other than incidental fallback within, the waters of the United States."[34] The term includes:

> any addition, including redeposit other than incidental fallback, of dredged material, including excavated material, into waters of the United States which is incidental to any activity, including mechanized landclearing, ditching, channelization or other excavation.[35]

Because the agencies did not define the term "incidental fallback," there is no bright line between what constitutes a redeposit and what is considered non-regulated incidental fallback. Thus, whether a particular activity (for example mining excavation) would be considered a discharge of material under Section 404 must be decided on a case-by-case basis.[36] The specific equipment and operating methods employed to move materials in wetlands or other regulated areas must be carefully evaluated to determine the applicable permit requirements and conformance with EPA and Corps policies.

In general, to obtain a Section 404 permit, "applicants must demonstrate that the discharge of dredged or fill material would not significantly degrade the nation's waters and there are no practicable alternatives less damaging to the aquatic environment."[37] Activities that do not conform to applicable standards are deemed contrary to protection of public trust resources and will not be authorized.

There are several ways in which activities in wetlands can be authorized under Section 404:

First, under Section 404(e), the USACE may issue general permits on a nationwide, regional or statewide basis for categories of activities that are presumed to cause only minimal adverse environmental impacts. USACE has identified and periodically updates a list of categories of general permits.[38] Some general permits require that an applicant notify the USACE prior to commencing activity in a wetland.

Second, the USACE may issue a letter of permission for activities not covered by a general permit if the USACE determines the "proposed work would be minor, would not have significant individual or cumulative impact on environmental values and will not encounter appreciable opposition."[39] Typically, notice of the proposal must be given to concerned fish and wildlife agencies, and property owners who might be affected by the proposal. There is no public notice or comment period for a letter of permission.

Finally, USACE may issue an individual permit to authorize specific site activity as detailed in a permit application. An individual permit may be issued if, after a public notice and comment period, the USACE determines that the proposed activity is not contrary to the public interest.[40] After receiving a completed permit application, the USACE will issues a public notice within 15 days.[41] The public notice must describe the proposed activity, its location and potential environmental impacts of the proposed activity. The USACE will invite public comment on the proposed activity.

USACE reports that on average, the time frame for permitting under Section 404 is:

- Two to six months from receipt of a completed application for individual permit decisions (standard permits and letters of permission); and
- Less than 30 days for decisions regarding general permits.[42]

One other significant review factor that can affect the terms and conditions of an individual permit, whether the permit may be issued and certainly the application review period is consideration of all such permit application pursuant to the National Environmental Policy Act (NEPA) (42 U.S.C. 4321 *et seq.*). NEPA applies to the federal permitting program for both Section 402 and Section 404 permits. In some cases, a reviewing agency may determine that additional detailed information or evaluation is not required to satisfy the NEPA review standards. The agency may conclude that it has sufficient information in the application materials to determine there is little risk of substantial environmental impacts from the project. In such cases, the preparation of an environmental assessment (EA) satisfies the NEPA process and the application review process typically is not substantially delayed. In other instances where sensitive resource impacts are a consideration or the scope of the project or public interest factors are a significant concern, an agency may need to conduct a more demanding NEPA review and prepare a detailed environmental impact statement (EIS) as part of the application review process.[43] In such cases, USACE estimates that the application process would take an average of three years.

4.4.7 Clean Water Act Enforcement

If an entity discharges pollutants without a CWA Section 402 permit or in violation of its permit, such violators may be subject to enforcement by the EPA. With respect to violations under CWA Section 404 (wetlands permit matters) the EPA and USACE generally operate under a memorandum of understanding (MOU) that is used to coordinate their enforcement efforts and determine which agency will pursue particular matters. While case by case decision may be made, the MOU suggests that EPA would be the likely lead agency to enforce against those who conducted regulated activities without a permit, while USACE would take the enforcement lead for violation of the terms of a wetlands dredge or fill permit.

The agencies may prosecute a violation under a number of enforcement mechanisms. For example, the agencies may issue an administrative compliance order, seek court-imposed civil penalties or, under certain circumstances, institute a criminal judicial proceeding.

Under Section 309 of the CWA, the EPA may issue an administrative order where an entity is in violation of the CWA or an NPDES permit.[44] Administrative orders issued by the EPA generally require the violator to cease the unauthorized activity and/or take remedial steps to correct the violations. Similarly, USACE may issue a "cease and desist" order for certain violations.
Both the EPA and USACE also have the authority to impose administrative penalties. CWA violations and penalties are generally divided into two categories: Class I and Class II.[45] Class I penalties are imposed for less egregious violations. For a Class I violations, the EPA may impose a penalty up to $16,000 per violation (not to exceed $37,500). Class II penalties allow the EPA to impose a penalty up $16,000 per day for each day during which the violation continues (not to exceed $177,500).

In addition to the administrative remedies, the U. S. Department of Justice may commence a civil or criminal suit in federal court on behalf of the EPA or USACE. Unlike the administrative enforcement authority of the agencies, while there are penalty limits for each violation, the authority held by a court to issue a monetary penalty is only limited by the number of violations and days of violations discovered. In a civil action, the Department of Justice may seek injunctive relief and/or civil penalties. Civil penalties may be awarded in the amount of up to $37,500 per day per violation.[46] Further, the CWA permits criminal prosecution of negligent violations, knowing violations and knowing endangerment of others.[47] Penalties for negligent violations generally include a fine of up to $25,000 per day per violation and/or imprisonment for not more than one year. A knowing violation may result in a fine of up to $50,000 per day per violation and/or imprisonment for not more than three years. An entity that knowingly endangered others may be subject to a fine of up to $250,000 and/or imprisonment up to 15 years for an individual or up to $1,000,000 for an organization. Finally, under certain circumstances, citizens may directly initiate enforcement actions under the CWA to seek injunctive relief and penalties.[48]

4.5 Groundwater

Groundwater is one of our most valuable resources. The most importance use of groundwater is as a drinking water source. Comparatively larger quantities of groundwater are used for non-potable purposes such as irrigation, residential and commercial heating and air conditioning, power generation and for various industrial purposes. According to the U. S. Geological Survey[66], "About 23 percent of the freshwater used in the United States in 2005 came from groundwater sources" and approximately 68 percent of the fresh groundwater withdrawals were for irrigation in 2005.

Over approximately the past 20 years, recognition of the importance of groundwater as a source of discharge to surface water bodies, such as rivers, lakes and wetlands has been increasing.

With this recognition, groundwater and surface water need to be considered as a single interconnected resource.

The aggregates industry is required to verify that water resources are being used beneficially and that the resources are protected. Loss or impairment of this important resource can occur through degradation of groundwater quality and decrease in groundwater quantity. For aggregates extraction operations where dewatering is employed, loss of groundwater quantity is usually the more important concern, although commonly the public perception is that degradation of groundwater quality is an equally important concern.

4.5.1 Groundwater Quality

The process of aggregates extraction results in the stripping of topsoil layers and unusable overburden and a decrease in the separation between the ground surface and groundwater. For cases of quarrying in karst terrain[67] or where extraction is extended to or below the groundwater table, a direct pathway to groundwater exists. Because these factors increase the potential for groundwater contamination from a release of chemicals at the ground surface, control of chemicals that could potentially impact groundwater is very important in aggregates extraction operations. Possible sources of groundwater pollution include:

- Accidental surface spills of chemicals such as solvents or fuels
- Leaking underground storage tanks
- **Unregulated** waste disposal

Responsible attention to these sources minimizes the threat of groundwater contamination.

Accidental surface spills can be controlled by storing all chemicals and petroleum products in designated concrete or impervious material storage areas so that accidental spillage is contained within a diked or bermed area. Any spilled chemical product or waste material can then be collected and given proper disposal. Where above ground oil storage capacity is greater than 1,320 gallons or underground oil storage capacity is greater than 42,000 gallons, a Spill Prevention Countermeasure Control (SPCC) Plan required by regulatory agencies must be kept at the site and all personnel must be familiar with the designated procedures.

EPA regulations specify mandatory underground tank testing programs, as well as guidelines for the installation of new tanks to ensure early detection of any leakage. Care must be taken to adhere to all applicable federal, state and local regulations regarding underground tank installation and operation. The regulations should be reviewed periodically to maintain compliance with revisions.

Hazardous substance and waste management requires concerted efforts to minimize the handling and disposal of materials with the potential to cause groundwater contamination. The mine operator must be aware of the composition of the materials used and their potential impact upon the environment if released. Often alternate sources of materials are available which are classified as non-hazardous and, where possible, non-hazardous substitutes should be utilized. Care must be exercised when handling hazardous materials. The operator of a mine should ensure that a subcontractor responsible for disposing hazardous waste is:

- Reputable
- Disposing the material at a licensed site or recycling center
- Handling the material in accordance with all EPA, state and local regulations
- Licensed to transport the material
- Documenting the disposition of the hazardous material
- Properly covered with liability insurance

In addition to the contaminated concerns related to the storage and use of chemicals, water quality concerns associated with mine operations related to bacteria, turbidity and water temperature may be raised. It is not uncommon for neighbors of a rock quarry to complain about turbid or muddy water from a production well thought to be a result of quarry blasting. In a 2005 study conducted by the Minnesota Department of Natural Resources[68], concern was raised with large open water bodies in sand and gravel operations raising groundwater temperatures. A discharge of turbid water or warm water from a mine operation can affect the health of the local receiving stream. Discharge of water from the operation is covered further under Section 4.4 Surface Water Quality.

When necessary or desired, groundwater quality can be assessed by utilizing groundwater monitoring wells or through sampling surface water and water-supply wells. Monitoring wells are used to measure fluctuations in the water table and for sampling groundwater for water quality testing.

4.5.2 Groundwater Quantity

Groundwater is obtained from an aquifer, a water-bearing unconsolidated or bedrock geologic formation which stores and transmits water. The term aquifer is usually restricted to water-bearing formations that can yield a sufficient supply of water to a production well. Soil and bedrock types that are commonly aquifers such as sand and gravel, limestone and dolomite, sandstone and igneous and metamorphic bedrock are also the targets of aggregates production. The quantity of water available in an aquifer and the potential groundwater impact that can result from mining below the water table are dependent on the hydrogeologic properties of the aquifer.

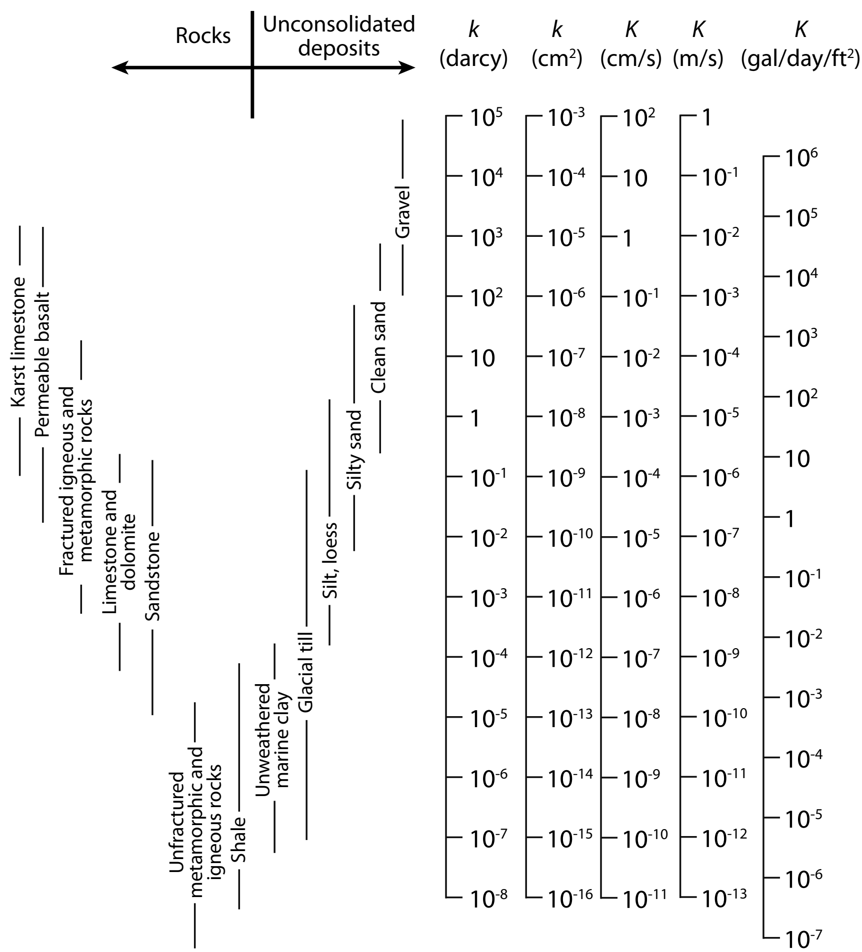
4.5.2.1 Hydrogeologic Properties

The amount of groundwater that can flow through soil or bedrock depends on the amount of voids and the interconnection of voids in the soil or rock. Porosity is a measure of the amount of voids and typically ranges from 1 percent to 50 percent. The voids in sand and gravel and sandstone are called pores and the voids in fractured rock such as limestone, dolomite and igneous and metamorphic rock are called fractures and joints. Typical porosity values are shown on the Table 4.1. Hydraulic conductivity or permeability is a measure of the degree of connection between the voids and can vary over a range of up to 14 orders of magnitude. Typical hydraulic

Table 4.1 Typical Ranges of Porosity Values[69]

Unconsolidated deposits	n (%)	Rocks	n (%)
Gravel	25-40	Fractured basalt	5-50
Sand	25-50	Karst limestone	5-50
Silt	35-50	Sandstone	5-30
Clay	40-70	Limestone, dolomite	0-20
		Shale	0-10
		Fractured crystalline rock	0-10
		Dense crystalline rock	0-5

Table 4.2 Typical Ranges of Hydraulic Conductivity Values[69]



conductivity values are shown on the Table 4.2. Aquifers both store (are porous) and transmit (are permeable) groundwater in sufficient quantities to supply a production well. Fine-grained geologic materials such as clay or shale, which consists primarily of clay, have many small pores (are porous), but the pores are not well connected (have low permeability) and are known as aquitards because they restrict ground water flow. Unconsolidated and bedrock aquifers have very low clay content and as a result, they are also commonly the target for extraction as an aggregates resource.

While unconsolidated deposits and bedrock formations that are on the higher end of the permeability ranges make the best aquifers and are also commonly the target for aggregates production, they also have the greatest potential for groundwater impact if dewatering is performed to facilitate extraction from the mine.

4.5.2.2 Dewatering

Dewatering or pumping of groundwater from the extraction operation is performed to allow the extraction of reserves that exist below the water table to occur in a dry state. The amount of groundwater that enters a mine and the extent to which water levels can be drawn down from dewatering at a mine is related to the depth to which the water level is maintained below the surrounding water table and the permeability of the aquifer among other factors. Dewatering can detrimentally affect water levels in neighboring production wells and in the discharge to area surface water bodies and wetlands as described below in Sections 4.5.2.3 and 4.5.2.4. Predictions of dewatering flow rates, and size and shape of the cone of depression can be made with analytical equations or digital groundwater modeling using hydraulic information available in literature or from performing aquifer pumping tests on the prospective mine site.

Dewatering of sand and gravel will commonly result in a relatively uniform cone of depression due to relatively uniform aquifer properties in sand and gravel deposits and the prediction of dewatering flow rate and cone of depression can be made with relative accuracy for a sand and gravel deposit. Because dewatering rates in a sand and gravel deposit can be very high and the cone of depression large with the potential to encompass a large area outside the mine property containing domestic water supplies and because sand and gravel can be extracted with relative ease from below the water table using an excavator or dragline without lowering the water table, dewatering for extraction of sand and gravel is not common.

Where groundwater is present in fractures in bedrock such as limestone and dolomite, dewatering rates are much less predictable than for sand and gravel. Dewatering in fractured bedrock will commonly result in a preferential orientation and sometimes unpredictable shape of the cone of depression. Predicting dewatering rates in fractured insoluble igneous and metamorphic bedrock is also difficult but typically much less of an issue for the operation than for dolomite and limestone because the groundwater inflow rates and cones of depression may be smaller due to the lack of solution-enhanced features in insoluble bedrock. The unpredictability of groundwater inflows and shape of drawdown cone in fractured bedrock is a result of the variability in hydraulic properties of fractured bedrock both laterally and with depth and the orientation, size and continuity of bedrock fractures.

There are a number of exploration techniques to help evaluate fractured bedrock characteristics, such as photo-lineament analysis with aerial photographs, geophysical surveys using a variety of methods, fingerprinting of water sources to the mine, corehole logging, drilling and well installations and performance of pumping tests. However, for most of the exploration techniques, the scale of information is insufficient to provide precise locations of fracture features and precise predictions of groundwater inflow and drawdown cones. Implementing investigation and pre-planning tasks within the mine planning process are recommended proactive measures to minimize catastrophic flooding events.

In bedrock which is at or near the ground surface and which is highly susceptible to dissolution (for example, limestone), karst features such as solution enlarged fractures and caves commonly develop. In well-developed karst terrains, a majority of the groundwater will flow in major karst conduits and predicting the rate of groundwater flow into a quarry and the effect on the groundwater system with accuracy can be impossible. Groundwater inflow rates are highly variable both laterally and with depth. For example, dewatering rates can increase from hundreds of gallons per minute to many thousands of gallons per minute with a single rock blast that opens a major karst feature. Diverting groundwater flow from a major karst feature into the mine can also have the effect of drying up or reducing flow to production wells and springs whose source of water is the same or connected karst conduit.

A major increase in groundwater inflow can occur in a sand and gravel operation when the mine is excavated through a deeper low permeability clay layer (aquitard) into a permeable sand and gravel layer with groundwater elevations much higher than the surface elevation of the confining clay layer. In this case the deeper sand and gravel deposit is under pressure due to the overlying clay layer and penetration of the clay layer allows groundwater to rapidly flow into the mine due to the penetration of the confining unit. A similar event can occur in bedrock when mining below the water table through a lower permeability portion of the bedrock (aquitard) such as a cherty or shale layer in limestone or dolomite into a higher permeability section where groundwater is under pressure. Because a bedrock mine can be advanced hundreds of feet below the water table, very high groundwater pressures can be present beneath the mine if a low permeability layer is present and very high groundwater inflow rates can occur when the low permeability layer is penetrated through blasting.

In addition to the potential large-scale impacts to groundwater levels from dewatering in karst terrains, another consideration for dewatering in karst terrains is the potential for enhanced sinkhole development resulting from dewatering activities. As shown in Figure 4.6, sinkhole development is enhanced by loss of buoyant support in the overburden from groundwater, volume shrinkage of the overburden from drying, washout of the overburden through piping or induced recharge and increased groundwater flow velocity through karst features.

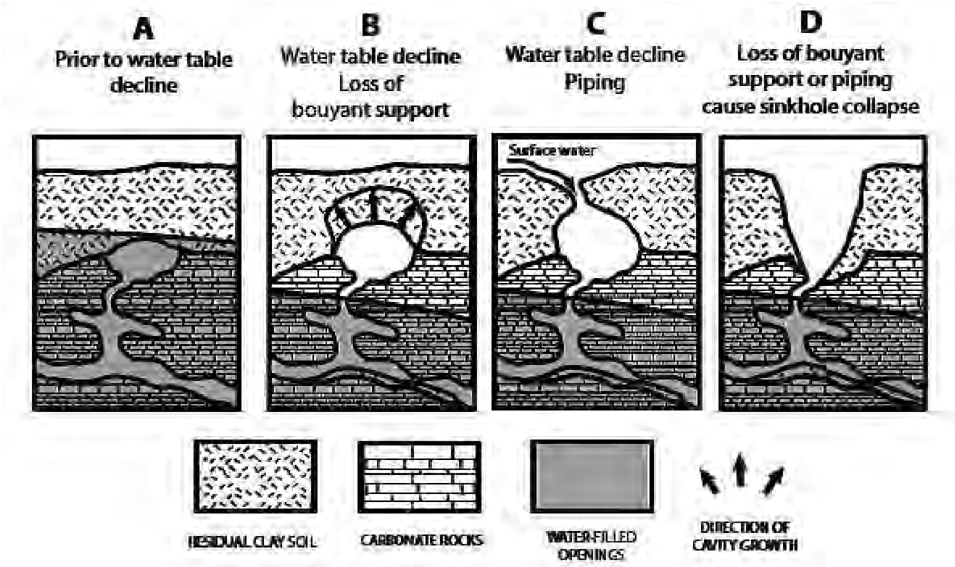


Figure 4.6 Diagram Showing Mechanics of Sinkhole Development[70]

4.5.2.3 Potable Water Use

Because of the difficulties in getting mines permitted in developed areas, many mines are developed in rural areas outside of incorporated municipal areas where a municipal water supply is not available and the neighboring residential properties have self-supplied water systems. According to the USGS[66] "over 98 percent of self-supplied domestic water withdrawals came from groundwater." Commonly the neighbors of mines obtain their water supply from the same unit (aquifer) targeted for extraction by the mining company. Therefore, there is a reasonable potential that an aggregates extraction operation that requires dewatering will impact the local domestic water supply. In advance of developing the mine, the operator can assess the potential affect on groundwater through aquifer testing (pumping tests) to evaluate aquifer properties and analytical and digital groundwater modeling to predict the impact to groundwater resulting from dewatering activities. An inventory of the producing zones and depths of area water-supply wells, commonly found on well construction reports available online in many states, along with the groundwater drawdown predicted to result from planned dewatering at the operation will allow the mine operator to evaluate potential detrimental affects to neighboring water supplies.

When partial or full loss of water supply or changes in water quality are observed by the owners of a domestic water supply near the mine, the operator is commonly contacted by the owner immediately with a request to restore the water quantity or quality or to pay the bill for work conducted by a drilling contractor. There are many potential causes of loss of water quantity or impairment of water quality in a domestic well other than dewatering at a mine such as water-supply pump malfunction; loss of conductor pipe integrity; pressure tank malfunction; seasonal water-level variations; other pumping centers such as dewatering for construction or other mines; municipal, industrial and irrigation high capacity production wells; iron or sulfur bacteria in well or water system; cracked or degraded well casing; barnyard or farm field runoff; etc. In certain circumstances where there are many local domestic wells with the potential to be impacted by dewatering of a mine, the mine operator should consider establishing a groundwater monitoring well network to aid in establishing causes of adverse well affects or to allow an advance notice that adverse groundwater impacts are occurring in the aquifer as a result of dewatering.

As described in Section 4.5.2.2., release of hydraulic pressure due to mining through a low permeability layer can result in nearly instantaneous and far reaching and substantial declines in area water levels with the potential to affect groundwater availability to domestic production over a large area. Investigation in advance of mining and while the mine is advanced can provide prior indications of whether this potential exists at a site. In the event of such an occurrence, the mine operator needs to be prepared to restore water to the affected properties on an emergency basis.

4.5.2.4 Sensitive Ecosystems

Sensitive ecosystems that depend on a source of groundwater to various degrees include such features as wetlands, rivers and lakes. The supply of water required to maintain a wetland can come from surface water, groundwater or a combination to surface water and groundwater. If the wetland is maintained primarily or exclusively from surface water, the health of the wetland can be affected through changes in surface drainage patterns over the area that supplies runoff to the wetland. A wetland that depends primarily on groundwater as its water source is sensitive to changes in water table elevation as the water level in a wetland needs to be maintained near the ground surface. If the groundwater supply source for the wetland is connected to the water source being dewatered for operation of a mine, the potential for the mine to affect the health of the wetland exists. While dewatering activities can affect the availability of water to both a domestic well and a wetland, in many cases the effect to the wetland is of a greater issue due to the need to maintain the water table elevation near the ground surface while in most cases, the quantity of water can be restored to the domestic well owner through deepening of the well and/or lowering of the pump.

In a similar way as with wetlands, the potential affect of mine dewatering on a river (in the context of this section river is used to refer to the full range of drainages from unnamed intermittent drainages to large regional rivers), spring or lake is dependent on the source of water to the river, spring or lake. Rivers receive all their water supply from runoff if groundwater remains deeper than the streambed throughout the year. However, most rivers derive a portion of their flow from groundwater discharge.

A river that is primarily groundwater-fed or a river that is under baseflow conditions is more likely to be affected by lowering of the water table than a river receiving a large proportion of surface water discharge. Baseflow occurs when the river is receiving its water supply almost exclusively from groundwater discharge and flow is near the low end of its flow range. Whether mine dewatering has the potential to have a noticeable or significant effect on a river's flow rate is dependent on dewatering rate compared to the river discharge rate and the portion of the river's drainage basin affected by the mine dewatering. Dewatering of a mine located near a river's headwaters has a greater potential to affect flow rate because the recharge area near a river's headwaters is small. Similarly, the potential for mine dewatering to affect a lake is dependent on the proportion of a lake's water supply that comes from groundwater. Decreasing the groundwater flow contribution to a lake can affect lake water level and water turnover rate.

Wetlands are commonly present along rivers, especially those that are slow-moving and meandering and lakes. Although the riverine and lakeshore wetlands usually will receive some groundwater discharge, they are more dependent on the river or lake to maintain the water level in the wetland and typically have less potential to be affected by dewatering activities.

4.5.2.5 Best Management Practices

A number of operational issues can be implemented to minimize the potential effects of mining on groundwater. From the groundwater quality perspective, implementation of chemical storage and use and minimizing of the use of hazardous chemicals as discussed in Section 4.5.1 will go a long way toward minimizing the potential for detrimental effects to groundwater quality. From the perspective of minimizing the potential effects of mining on groundwater quantity or to mitigate the detrimental effects, the following practices should be considered:

1. From the big picture area zoning standpoint, clustering mines together can limit the groundwater dewatering rates for any one particular operation in the cluster and greatly reduce the total rate of groundwater pumped from widely spaced operations that do not have overlapping groundwater cones of depression.

2. For mining sand and gravel, the practice of below water-table extraction using a dragline, clamshells or backhoe has largely replaced dewatering and dry-bank mining of sand and gravel deposits, and has nearly eliminated the groundwater quantity impacts of sand and gravel pits.

3. Operation of bedrock quarries without dewatering when groundwater quantity impacts are unacceptable or the groundwater inflow may be too great to be pumped should be considered. In that case, operation dewatering is minimized, the rock drilled and blasted below the water table and the blasted rock removed using draglines, clamshells or other equipment.

4. Where water enters a operation from a limited number of well-defined fractures or karst features, a focused grouting program to minimize the high groundwater inflow areas can be considered, but the success of implementation is uncertain. For large quarries with numerous inflow locations throughout the operation, grouting is unlikely to be economically feasible.

5. In order to conserve groundwater resources, artificial recharge of aquifers using the water pumped from the operation can be considered. Regulatory approval, sufficient area to allow for infiltration and consideration for water to return to the quarry and increase dewatering rates are all challenges that need to be overcome in this approach.

6. Where a groundwater resource may be insufficient for municipal needs, use of treated operation water for direct use in a municipal water supply could be considered.

7. When dewatering causes undesirable impact to a wetland, water pumped from the operation could be considered for diversion to the affected wetland to maintain adequate water levels in the wetland.

8. Water can be conserved through re-use in the aggregates washing process, for dust control on the mine site or for use in irrigation of area croplands.

4.5.2.6 Regulatory Requirements and Permitting for Groundwater Use

Many states have developed specific permit programs to regulate the use of groundwater and surface water resources. These programs typically do not apply to those operations that obtain their water from municipal water departments or water companies. The consumptive use of groundwater withdrawn for process operations may require a "diversion" permit as well as permits under other federal or state programs. For example, in Ohio a permit is required from the Ohio Department of Natural Resources for the diversions of water out of either the Lake Erie or Ohio River Basins in quantities greater than 100,000 gallons per day.[54A] Similarly, in Kentucky, a permit is required to withdraw, divert or transfer "greater than 10,000 gallons [of water] per day from any surface, spring or groundwater source. Certain exceptions have been created for water required for domestic purposes (needs for one household); agricultural withdrawals, including irrigation; steam-powered electrical generating plants whose retail rates are regulated by the Kentucky Public Service Commission or for which facilities a certificate of environmental compatibility from such commission is required by law; or injection underground in conjunction with operations for the production of oil and gas."[55A] There also may be general permits that authorize specified uses of surface water or groundwater that meet criteria concerning the volume used, source of supply, operating requirements, reporting standards and compliance with emergency suspension of operations during water emergencies or drought declarations. If you plan to divert water, it is critical that you determine whether a permit is required and, if so, what type of permit should be obtained. Many states have developed detailed permitting programs for the diversion (use) of water. Some states also have a long history of addressing water rights in court decisions as well as modern day permit programs. Any facility managers that anticipate the need to obtain their own source of water should be sure to examine state permitting requirements and applicable common law (court decisions).

Similar to other permitting programs, there may be general permits available for some groundwater uses in addition to program standards for securing an individual permit to authorize groundwater withdrawals. The use of general or individual permits often is affected by the volume of water to be used, the specific source, anticipated environmental impacts, potential impacts to other users and the purpose of the withdrawal.

Many states also have developed water classification systems based on the quality of the water resource, historical uses, impacts and permitted future uses. These classifications may restrict or preclude certain activities that may affect water quality in areas where water is used as a drinking water resource. The EPA also has developed water classifications. In 1988, the EPA finalized its Guidelines for Ground-Water Classification Under the EPA Ground-Water Protection Strategy.[51] The EPA's ground-water classification system consists of three general classes of ground water, representing a hierarchy of the values ground-water resource have to society.

These classes are the following:

- Class I: special ground water
- Class II: ground water currently and potentially a source for drinking water
- Class III: ground water not a source of drinking water

While the EPA classifications are generally utilized to determine environmental cleanup obligations, they also may parallel programs adopted by many states toward a prioritized approach to groundwater use.

As mining operations often divert water and may occur in areas where groundwater is necessary for human consumption, each company should review its state-specific regulatory requirements to determine whether a diversion permit would be required for its planned activities.

4.6 Air Quality

The quality of the air we breathe has been a primary concern of American society and all levels of government for many years. During the last 40 years, however, the general public and its political leadership have become acutely aware of air pollution and have taken significant steps to protect and preserve overall air quality. A multitude of federal, state and local laws and regulations have been developed and put into place to address this issue. These various statutes and their enabling regulations define the nation's air quality goals (i.e., the levels of acceptable pollution which have a minimal effect on public health). The means to achieve these goals are expressed in the form of performance standards or permissible emission levels.

One air quality issue of concern to aggregates producers relates to particulate matter or dust. Pit and plant operations are by their very nature dusty operations unless adequate suppression of dust emissions is achieved. Fortunately, most of the emissions are large, heavy particulates that settle within the plant property; thus the industry is not generally considered a major source of air pollution. Figure 4.7 depicts the rapid settling of the dust emissions associated with pit and plant emissions. Pit and plant related dust emissions generally range in size from about 0.1 micron to more than 300 microns in diameter (74 microns = No. 200 sieve size, 44 microns = No. 325 sieve size, one micron = 1/25,000 inch). Only limited data are available on particle size distributions of the dust generated at these operations. However, the data illustrated in Figure 4.8 demonstrate the relative coarseness of the particulates involved. Given their size and weight, therefore, the typical dusts associated with aggregates operations are more of a nuisance than a health impact on the ambient atmosphere.

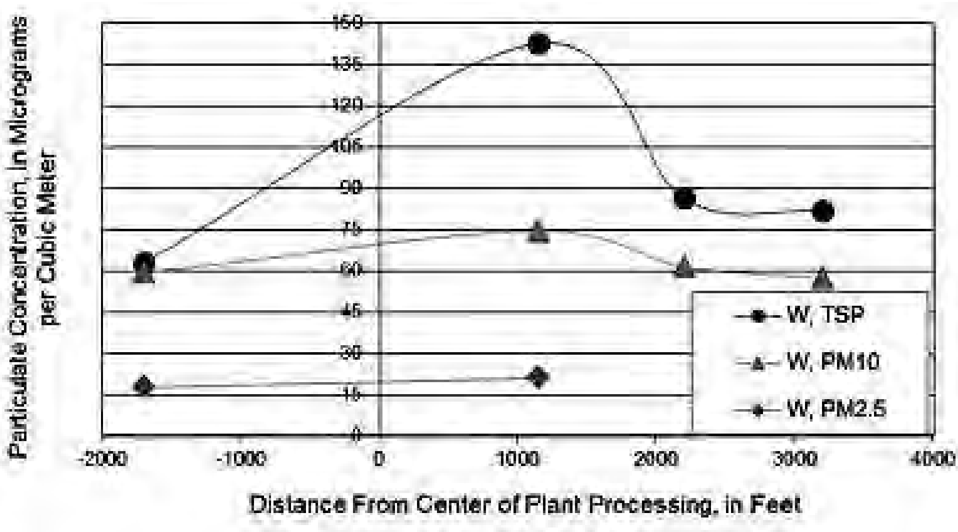


Figure 4.7 Concentrations of Dust Downwind of a Stone Quarry

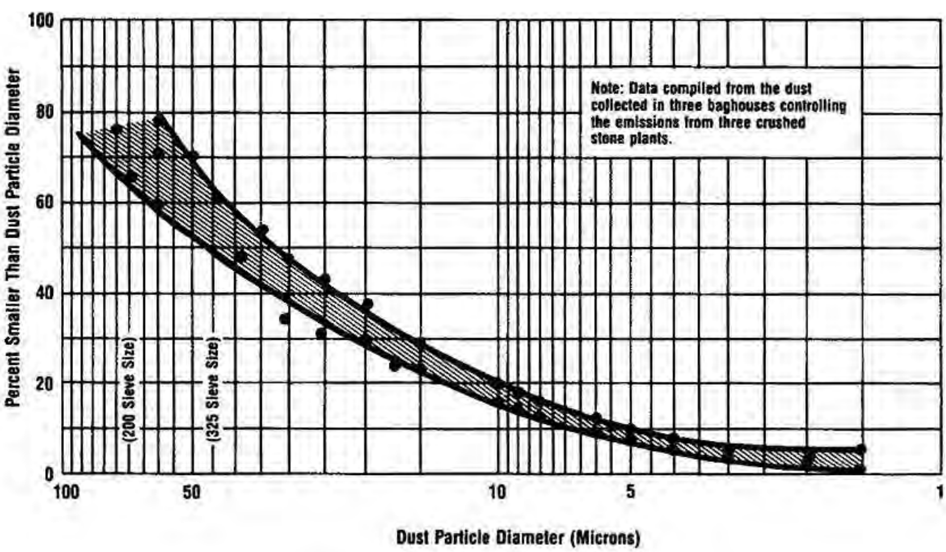


Figure 4.8 Particle Distribution of Dust Collected from Three Baghouses

Emission Sources: Many operations conducted within these facilities has a potential to emit dust to the atmosphere. The operator's task is to minimize or otherwise control the emissions from these various sources. The crushing, conveying, screening and stockpiling taken together is referred to as the *plant generated dust sources*. The blasting operations, the haul roads in and around the site and the stockpile storage areas give rise to what often is termed *fugitive dust emissions*. These two major types of emission sources lend themselves to different control techniques.

Plant Emissions: The plant generated emission sources can be hooded, vented or otherwise enclosed and their resulting emissions directed to a mechanical (*dry*) collecting device which removes the dust particles before release of the air stream to the atmosphere. More commonly, however, the plant generated sources are controlled through use of a *wet suppression system*, which consists of a series of high pressure water sprays located throughout the process stream. The high pressure sprays function in a manner to keep dust from becoming airborne. A combination of the two systems is also employed in some instances. Both dry collection and wet suppression are capable of control efficiencies in excess of 95 percent.

Fugitive Emissions: The fugitive generated emissions are typically controlled by a combination of control equipment and housekeeping practices exercised by the plant operator. Control equipment would include such things as the use of a water truck on all roadways and around the stockpile area, the use of stockpile sprinkling systems and various products designed to stabilize road surfaces. Housekeeping practices would include the control of vehicle speeds, the use of a mechanical sweeper on paved areas, the proper use of wind breaks, the proper use of seeding and plantings in open areas and a multitude of other techniques are the keys to success in the control of fugitive emissions.

Wet Dust Suppression: The most commonly used dust control device is a wet suppression system. Wet dust suppression uses a pressurized liquid for the controlled reduction or elimination of airborne dust or the suppression of such dust at its source. Effective control involves:

1. Confinement of the dust within the dust producing areas by a curtain of moisture;
2. Wetting of the dust by direct contact between the particles and droplets of moisture; and
3. Formation of agglomerates too heavy to remain airborne or too heavy to become airborne.

The wet suppression system of dust control is particularly suitable to processing plants since it does not involve hoods or other enclosures for crushers, screens or conveyor transfers. The equipment remains open and accessible for maintenance and the operator can readily observe all equipment and material flow.

Spray application must be located at critical points throughout the processing plant, such as at the primary crusher feed point, all crusher discharge points, conveyor transfer points and sizing screens. A schematic drawing of a processing plant with a wet dust suppression system is shown in Figure 4.9. A more complete description of the operation and design characteristics of wet suppression systems is given in Chapter 8.

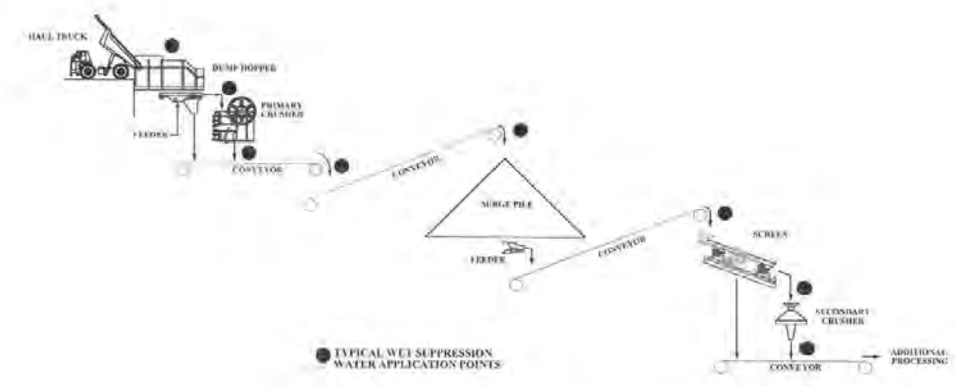


Figure 4.9 Rock Crushing Plant West Dust Suppression System

Dry Dust Collection: The most commonly used dry collection system at processing plants is the fabric *filtering system*. It is a local exhaust control system consisting of four major elements: hoods, ducts, fan and dust collection equipment (often referred to as a "baghouse"). Each dust emission source must be hooded or enclosed so that a large flow of air can be moved across the emission point and the air/dust mixture exhausted through ductwork to the control equipment (i.e., the baghouse). The baghouse is a large structure enclosing a series of fabric filter bags or cartridges through which the dust laden air is moved prior to release into the atmosphere. The filter bags or cartridges remove the dust from the air stream and the dust in turn is removed from the collectors and disposed of or reused in some fashion. Cartridge filter systems are starting to become more common than bag filter systems because of the ease in changing the filters and the reduced employee exposure to dust during the changes. Discussion of hood, duct and collector design is given in Chapter 8. Suffice it to say that the proper design of each element of a dry collection system is critical to achieving the desired control efficiency.

Combination Dust Collection Systems: Combinations of wet suppression and dry collection systems (refer to Figure 4.10) have been successfully employed when conditions dictate. A combination system is suggested for consideration for the following types of applications:

1. Where the fine particulates have an economic value and product recovery could be intrinsically profitable in addition to meeting local air pollution control requirements.

2. If *screen blinding* in secondary plant production occurs due to capillary tension as a result of moisture applied by a wet suppression system. Screen blinding, as used here, is the clogging of a screen due to particles sticking together when a small amount of water has been added. Blinding does not occur if a large quantity of water is used. Blinding also can be caused by the presence of clay or insufficient vibratory action to keep large particles from blocking the screen.

3. When, as a result of plant location or local pollution control codes, a high degree of dust control is required that is not economically feasible with a single type system.

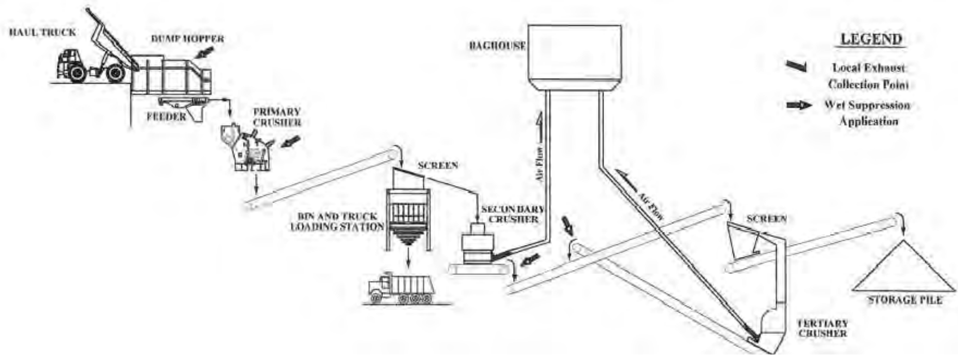


Figure 4.10 Typical Control System for Crushing Plant

Fugitive Dust Emissions: The control of fugitive dust is a very complex and challenging problem. Fugitive emissions are generated both by natural phenomena and by man-induced causes. Fugitive dust is by far the largest potential contributor to the total dust problem at an operating site and, because of its very nature, the most difficult and time consuming to properly control. Unlike the plant-generated emissions, which lend themselves to point source control, fugitive emissions are generated by unstable sources such as the movement of men and equipment and the effects of wind and rain on the stockpile areas and those areas stripped free of vegetation. Proper control of fugitive dust includes:

- Use of water trucks, sprinkler systems, dust palliatives, sweeping and in some instances paving of interior roads;
- Proper use of windbreaks, both natural and artificial, to protect and screen sensitive areas;
- Strict enforcement of a material spill policy and on-site speed limits;
- Strategic placement of stockpile areas to shield them from wind movements; and
- The maximum use of protective vegetative cover for open areas.

In addition, to be effective, a fugitive dust control program requires a dedicated commitment each day to the practice of good housekeeping techniques.

Control Regulations: Federal clean air legislation has assigned the responsibility of establishing standards for air quality to the EPA. The EPA has defined the best available control technology for the aggregates industry and has issued this information in the form of guidelines for the individual states since the states have the primary responsibility for enforcement of air quality regulations. state and local enforcement agencies may, however, establish standards and regulations which differ from the EPA. Therefore, it is important to determine the specific rules and regulations (federal, state and/or local) which are imposed upon any operating facility.

Point Source: Plant-generated emissions which are hooded, vented and exhausted through a collection device have a definable point source of emission: the stack or flue of the collection device. Such point sources lend themselves to the physical measurement of the amount of particulate matter emitted per volume of air emitted to the atmosphere. Such emissions may be regulated in terms of grains per cubic foot of air emitted or in terms of pounds per ton of aggregates produced.

Testing: The necessary testing to determine initial and continuing compliance with the weight per unit volume type regulation is both costly and time consuming. Most control agencies, therefore, permit or specify the use of visible emission determination (EPA Test Method 9) at each point source (each crusher screen, conveyor transfer point, etc.). These procedures must be conducted by individuals specially trained to judge the percentage density or opacity of the point source. Regulations might permit a 10 percent or 15 percent opacity as determined by a standard method. Fugitive-generated emissions, including any emissions which escape collection devices, are also judged on the basis of a visible emissions measurement.

Permits: Most state and local environmental control agencies require some form of permit for the operation of any industrial facility capable of emitting to the atmosphere any substance deemed to be an air contaminant. Pit and quarry operations must, therefore, secure, maintain and comply with such permits and be subject to compliance inspections conducted by the permit issuing agency. Proper operation and maintenance of all control equipment and the practice of fugitive emission control must, therefore, be an integral part of daily operating practices.

All new and substantially modified aggregates operations must comply with the various requirements of the federal New Source Performance Standards and often environmental impact statements are required setting forth their anticipated effect on local air quality. The EPA publication *AP-42* contains information useful in estimating the potential dust emissions from these operations.

4.6.1 New Source Performance Standards (NSPS)

New Source Performance Standards (NSPS), are promulgated under 40 CFR Part 60. The general provisions were published in the *Federal Register* on December 6, 1975 (40 FR 58416) as Subpart A. Specific standards applicable to nonmetallic mineral processing plants were initially proposed on August 31, 1983 (48 FR 39566). The New Source Performance Standard (NSPS) for nonmetallic mineral processing plants was published as Subpart 000 on August 1, 1985 (50 FR 31337) and revised on February 14,1989 (54 FR 6680). NSPS Subpart OOO and the general provisions of Subpart A were revised on June 9, 1997 (62 FR 31351), on October 17, 2000 (65FR61744-01) and again on April 28, 2009 (74FR19294).

4.6.2 Nonmetallic Mineral Processing Plants

The NSPS rule for nonmetallic mineral processing plants provides:

- Rules for applicability of the standards and designation of affected facilities;
- Standards for particulate matter emitted from affected facilities;
- Monitoring, reporting and record keeping requirements; and
- Test methods and procedures for determining compliance with emission standards.

The regulatory standards limit particulate matter emissions from crushers, grinding mills, screens, bucket elevators, bagging operations, storage bins, enclosed truck and railcar loading operations and transfer points on belt conveyors. Operations not included under these standards are drilling, blasting, loading at the mine, hauling, drying, stockpiling, conveying (other than at transfer points), windblown dust from stock- piles, roads and plant yards.

Subpart OOO (40 CFR 31337) designates affected facilities as individual pieces of operating equipment (i.e., screens, crushers, etc. which are *unit operations*) manufactured, modified or reconstructed after August 31, 1983.

4.6.3 Record Keeping and Emissions Limits

Record keeping requirements of the NSPS general provisions (Subpart A as well as those of Subpart 000) require data to be recorded and notifications issued for individual operating units. The regulatory standards limit both fugitive emissions and stack emissions from affected facilities. Table 4.2 shows the appropriate standard based on the construction, modification or reconstruction date of the affected facility.

State regulatory agencies may require more restrictive opacity standards.

4.6.4 Emission Factors

An *emission factor* is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere by an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance or duration of the activity emitting the pollutant (for example, pounds of PM_{10} emitted per ton of stone crushed). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality. Emission factors are generally assumed to be representative of long-term averages for all facilities in the source category.

Emission Factor Uses: The passage of the *Clean Air Act Amendments of 1990 (CAAA) and the Emergency Planning and Community Right-To-Know Act (EPCRA)* of 1986 has increased the need for both criteria and hazardous air pollutant emission factors and inventories. The Emission Factor And Inventory Group of EPA's Office of Air Quality Planning and Standards develops and maintains emission estimating tools to support the many activities mentioned above. The EPA's *AP-42*[4] publication series is the principal means by which EPA documents its emission factors.

The general equation for emission estimation is:

$$E = A \cdot EF \cdot (1\text{-}ER/100) \qquad \text{(S4-1)}$$

Where:

E = emissions
A = activity rate
EF = emission factor
ER = overall emission reduction efficiency (%)

AP-42[4] emission factors and emission inventories have long been fundamental tools for air quality management. Emission estimates have a number of different important uses including the following:

- Development of emission control strategies;
- Determination of the applicability of permitting and control programs;
- Estimation of the effects of sources and appropriate mitigation strategies; and
- Other related applications by an array of users including federal, state and local agencies, consultants and industry.

AP-42 emission factors are often appropriate to use in a number of situations such as making source-specific emission estimates for area-wide inventories. Available inventories have many purposes including ambient dispersion modeling and analysis, control strategy development and in examining specific sources for compliance investigations. Emission factors are also used in permitting applications such as in applicability determinations and in establishing operating permit fees.

Particulate Matter: "Coarse fraction" particles are greater than 2.5 (g/m3) in diameter. The National Ambient Air Quality Standard for PM_{10} was promulgated in 1987. $PM_{2.5}$ or "fine particulate matter" is also a regulated air pollutant and is considered to be airborne particles with a nominal aerodynamic diameter of 2.5 micrometers (g/m3) or less. In 1997, EPA established annual and 24-hour NAAQS for $PM_{2.5}$. Every five years the EPA is required to review the NAAQS for possible revisions based on scientific and technical information.

EPA published the final rule that sets forth the initial air quality designations and classifications for the areas in the United States for the Fine Particle NAAQS in January 2005. The proposed rule to implement the Fine Particle NAAQS was published November 1, 2005 and describes requirements states must meet in their implementation plans for $PM_{2.5}$. The EPA defines *regulated air pollutant* to include any pollutant for which a National Ambient Air Quality Standard has been promulgated, which would include both PM_{10} and $PM_{2.5}$. Chapter 11.9.2 of AP-42 was updated in 2004 and includes emissions factors for $PM_{2.5}$, PM_{10} and total particulate matter.

Example 1: Plant Emissions Calculation

Calculate the PM_{10} emissions from a screening facility processing granite at 500 tons per hour with a wet suppression dust control system in operation. Table S4.1 shows the emission factor for controlled screening is EF = 0.00074 lb PM10 per ton of stone screened.

The activity rate A = 500 tons per hour of stone processed. In this example the overall emission reduction efficiency (ER) is 0 percent because the emission factor for controlled screening already has a emission reduction efficiency applied. Then substituting these values into equation (S4-1) gives:

$$E = (500\ t/hr) \cdot (0.00074 lbsPM10/ton) \cdot (F1\text{-}0/100)$$
$$E = 0.37\ lbs\ PM_{10}/hour$$

Note: Always work the units in the equation out each time to determine if the ones used are correct. In the above example, tons in the numerator and denominator cancel giving the units shown of lbs PM_{10} per hours. ER in %, when divided by 100 gives a unitless number.

Tons of PM_{10} emitted on an annual basis from an individual affected facility is derived by (1) annualizing the production rate of the affected facility, (2) multiplying by the AP-42 emission factor and (3) then dividing that product by 2,000 lbs/ton. Once again, work the units out to be sure unit conversions are correct. This procedure avoids making a very common mistake in engineering calculations.

Example 2: Plant Emissions Calculation

Once again calculate the PM_{10} emissions from a screening facility processing granite at 500 tons per hour. Consider, however, a facility that does not have either direct water sprays as dust suppression or sufficient carry-over moisture from previous wettings to adequately suppress dust emissions. For these conditions, use the uncontrolled emission factor from Table S4.1 of EF = 0.0087 lb PM_{10} per ton of stone processed. When using uncontrolled factors from AP-42, it is appropriate to add an estimated emission reduction efficiency. Also use an estimated emission reduction efficiency (ER = 75 percent) that reflects the effectiveness of the controls employed at that facility. Assume once again the activity rate A = 500 tons per hour of processed stone substituting the above quantities into equation (S4-1) gives:

$$E = (500\ t/hr) \cdot (0.0087\ lbs/ton) \cdot (1\text{-}75/100)$$
$$E = 1.0875\ lbs\ PM_{10}/hour$$

The absence of sufficient moisture in the screening facility used in this example resulted in emissions almost three times greater than when water was employed in Example 1.

An affected facility without either direct water sprays as dust suppression or sufficient carry-over moisture from previous wettings to adequately suppress dust emissions, must use the uncontrolled emission factors from Table 4.3 and apply an estimated emission reduction efficiency that best reflects the effectiveness of the controls employed at that facility.

Table 4.3 Emission Factors for Crushed Stone Processing Operations (English Units)

SOURCE	PM10 (lb/ton)	SOURCE	PM10 (lb/ton)
Screening	0.0087	Fines Crushing (Controlled)	0.0012
Screening (Controlled)	0.00074	Fines Screening	0.072
Primary Crushing	ND	Fines Screening (Controlled)	0.0022
Secondary Crushing	a	Conveyor Transfer Point	0.0011
Tertiary Crushing	0.0024	Conveyor Transfer Point (Controlled)	4.6 x 10-5
Primary Crushing (Controlled)	ND	Wet Drilling; Unfragmented Stone	8.0 x 10-5
Secondary Crushing (Controlled)	a	Truck Loading; Conveyor	0.0001
Tertiary Crushing (Controlled)	0.00054	Truck Unloading; Fragmented Stone	1.6 x 10-5
Fines Crushing	0.015		

a = No data available, but PM_{10} emission factors for tertiary crushing can be used as an upper limit for primary and secondary crushing
ND = No Data.

4.6.5 Fugitive Emissions

Fugitive emissions are defined as dust generated from open sources. Fugitive emissions are not discharged to the atmosphere in a confined flow stream as from a stack. Examples of fugitive dust sources include paved roadways, unpaved roadways, storage piles and aggregates handling activities.

Emissions Drift: The impact of a fugitive dust source on air pollution depends on the quantity of the dust particles emitted into the atmosphere and the particle size distribution. The potential drift distance of particles is governed by the initial ejection height of the particle, the terminal settling velocity of the particle and the degree of atmospheric turbulence. Equations for estimating emissions from fugitive dust sources are given in Chapter 13.2 of AP-42.S2 Example: Theoretical drift distance, as a function of particle diameter and mean wind speed, has been computed for fugitive dust emissions. Results indicate that for a typical mean wind speed of 16 km/hr (10 mph), particles larger than about 100 microns are likely to settle out within 6 to 9 meters (20 to 30 feet) from the point of emission such as the edge of a road. Particles that are 30 to 100 microns in diameter are likely to undergo impeded settling. These particles, depending on the extent of atmospheric turbulence, are likely to settle within a few hundred feet from a road or other source point. Particles smaller than about 30 microns, including PM_{10} have much slower settling velocities and are much more likely to have their settling rate retarded by atmospheric turbulence.

Table 4.4 NSPS OOO Fugitive Emission Standards

FUGITIVES			
Affected facilities that commenced construction, modification or reconstruction…	**Type of Affected Facility**	**Opacity Limit (%)**	**Required Compliance Demonstration**
…after August 31, 1983 but before April 22, 2008	All defined affected facilities[1] (except crushers)	10	• Initial performance testing
	Crushers without a capture system	15	• Initial performance testing
…on or after April 22, 2008	All defined affected facilities[1] (except crushers)	7	• Initial performance testing • Periodic inspections of water sprays and • Repeat performance test within 5 years for affected facilities without water sprays[2]
	Crushers without a capture system	12	• Initial performance testing • Periodic inspections of water sprays and • Repeat performance test within 5 years for affected facilities without water sprays[2]

Table 4.5 NSPS OOO Stack Emission Standards

STACK				
Affected facilities that commenced construction, modification or reconstruction…	**Control Device Collection Method**	**Particulate Matter Standard (g/dscf)**	**Opacity Limit (%)**	**Required Compliance Demonstration**
…after August 31, 1983 but before April 22, 2008	Dry Collection	0.022	7	• Initial performance testing
	Wet Collection	0.022	NA	• Initial performance testing and • Monitoring of performance parameters
…on or after April 22, 2008	Dry Collection	0.014	NA[3]	• Initial performance testing and • Monitoring of performance parameters, via: • Quarterly Method 22 or • Bag leak detection system or • Subject to Lime Manufacturing NESHAP
	Wet Collection	0.014	NA	• Initial performance testing and • Monitoring of performance parameters

1. Defined affected facilities include the following: grinding mills, screening operations, bucket elevators, transfer points on belt conveyors, bagging operations, storage bins, enclosed truck or railcar loading stations or from any other affected facility.

2. Affected facilities controlled by water carryover from upstream water sprays that are inspected according to the requirements in this Subpart are exempt from this 5-year repeat testing requirement.

3. For individual enclosed storage bins being controlled by dry control devices, a 7% opacity standard applies.

4.7 Waste Management

This chapter provides an overview of the regulatory programs and management practices applicable to waste materials generated by aggregates mining operations. This is meant to provide a basic introduction to waste management within the aggregates industry and is not intended to be used as a substitute for establishing a regulatory compliance program to address waste management requirements. The discussion of regulatory programs is not meant to be comprehensive and does not cover all regulations which potentially could apply.

4.7.1 Regulatory Requirements and Overview

As with other environmental regulatory programs, waste management is regulated at the federal, state and in some cases local levels of government. Aggregates operators need to review the waste management regulations at each of these levels of government for each operation to ensure that all regulatory requirements are identified and compliance programs are implemented. Aggregates operators must stay current with proposed and enacted changes in waste management regulations at all government levels to ensure that changes in the regulations affecting the operation are identified and steps are taken to ensure compliance with the new or modified requirements.

4.7.1.1 Federal Regulation of Waste Management Activities Under RCRA

The federal regulation governing waste material management is the Resource Conservation and Recovery regulation, which is the implementing regulation for the Resource Conservation and Recovery Act (RCRA). The original act was authorized by Congress in 1976 and has been expanded through a series of reauthorizations. The RCRA regulations are codified in the federal regulations under 40 CFR, with the requirements related to non-hazardous waste in Parts 239 through 259 and the requirements for hazardous waste in Part 260 through Part 299. The primary requirements that affect aggregates operations are located in the following sections:

- Part 260 Hazardous Waste Management System, General
- Part 261 Identification and Listing of Hazardous Waste
- Part 262 Standards Applicable to Generators of Hazardous Waste
- Part 273 Standards for Universal Waste Management
- Part 279 Standards for the Management of Used Oil
- Part 280 Technical Standards and Corrective Action Requirements for Owners and Operators of Underground Storage Tanks (UST)

The federal RCRA requirements provide a consistent framework for facilities engaged in waste generation and management. The RCRA requirements generally apply at the point that the materials no longer is usable and a decision to discard it has been made by the operator.

Materials that are being used for their intended purpose and that continue to be used are normally not classified as waste material. The remainder of this chapter focuses on the specifics of waste management within the aggregates industry.

4.7.1.2 State and Local Regulation

In addition to the federal RCRA regulations, a majority of the states have adopted their own waste management regulations. In some cases these regulations mirror or adopt the federal regulations directly, while in other cases the state and/or local regulation is considerably different from the federal requirements. The EPA is responsible for evaluating the adequacy of state and local regulations. In cases where the EPA is confident that the state or local regulations are at least as stringent as the federal requirements, the EPA will authorize the state or local agency to implement and enforce the waste management requirements in lieu of the federal EPA. Where the state/local regulations are not as stringent as the federal requirements the EPA will retain control of the program. Even after delegation of authority to the state/local agency, the EPA retains the right and ability to oversee the effectiveness of the state/local program and to enforcement the regulations unilaterally and independently from the state/local agency.

Aggregates operators must comply with the state and local waste management regulatory requirements as well as any federal requirements.

4.7.2 Generator Classifications

The waste management regulations applicable to generators of hazardous waste are contained in 40CFR Part 262, which defines the generator classification of facilities based on the amount of hazardous waste generated in a calendar month. The federal generator classifications and the waste generation thresholds that trigger each class are as follows:

- Large quantity generators are defined as facilities that generate more than 1,000 kg/month of hazardous waste.

- Small quantity generators are defined as facilities that generate between 100 to 1,000 kg/month of hazardous waste in a calendar month.

- Conditionally exempt small quantity generators are defined as facilities that generate less than 100 kg/month of hazardous waste.

The majority of the waste materials generated by aggregates production operations are not classified as hazardous waste and the materials that do meet the hazardous criteria are normally generated in quantities that allow the operations to be classified as either small quantity or conditionally exempt small quantity generators of hazardous waste. However, operations with large shops or other co-located businesses may generate sufficient quantities of hazardous waste to qualify as a large quantity generator. Aggregates operators track the quantity of hazardous waste being generated to ensure that the facility is properly classified by generator type. Facility changes that increase or decrease the amounts of hazardous waste being generated can affect the generator classification.

Table 4.6 Primary Requirements of Hazardous Waste Regulations by Generator Classification

	Conditionally Exempt Small Quantity Generators (CESQG)	Small Quantity Generators (SQG)	Large Quantity Generators (LQG)
Quantity Limits	≤100 kg/month ≤1 kg/month of acute hazardous waste ≤100 kg/month of acute spill residue or soil	Between 100 - 1,000 kg/month §262.34(d)	≥1,000 kg/month >1 kg/month of acute hazardous waste >100 kg/month of acute spill residue or soil
EPA ID Number	§§261.5(a) and (e) Not required §261.5	Required §262.12	Part 262 and §261.5(e) Required §262.12
On-Site Accumulation Quantity	≤1,000 kg ≤1 kg acute ≤100 kg of acute spill residue or soil §§261.5(f)(2) and (g)(2)	≤6,000 kg §262.34(d)(1)	No limit
Accumulation Time Limits	None §261.5	≤180 days or ≤270 days (if greater than 200 miles) §§262.34(d)(2) and (3)	≤90 days §262.34(a)
Storage Requirements	None §261.5	Basic requirements with technical standards for tanks or containers §§262.34(d)(2) and (3)	Full compliance for management of tanks, containers, drip pads or containment buildings §262.34(a)
Send To	State approved or RCRA permitted/interim status facility §§261.5(f)(3) and (g)(3	RCRA permitted/interim status facility §262.20(b)	RCRA permitted/interim status facility §262.20(b)
Manifest	Not required (§261.5)	Required (§262.20)	Required (§262.20)
Biennial Report	Not required (§261.5)	Not required (§262.44)	Required (§262.41)
Personnel Training	Not required §261.5	Basic training required §262.34(d)(5)(iii)	Required §262.34(a)(4)
Contingency Plan	Not required §261.5	Basic plan §262.34(d)(5)(i)	Full plan required §262.34(a)(4)
Emergency Procedures	Not required §261.5	Required §262.34(d)(5)(iv)	Full plan required §262.34(a)(4)
DOT Transport Requirements	Yes (if required by DOT)	Yes §§262.30-262.33	Yes §§262.30-262.33

The primary requirements of the federal hazardous waste regulations according to generator classification are listed in Table 4.6. This information is accurate as of the date of publication but the 40CFR Part 261 and state waste regulations should be referenced for compliance purposes as this information may have changed.

Some states have generator classifications that are different from the federal requirements. As an example, some states do not include the conditionally exempt small quantity generator classification in their waste management regulations. Aggregates operators need to be knowledgeable of the differences between their state and local regulations and the federal requirements to ensure that the applicable requirements are met.

4.7.3 Waste Minimization

The adoption and implementation of waste minimization techniques is a common way that the aggregates industry recognizes value in the waste management area. Some of the values that can be recognized include the following:

- Reduction in material procurement cost by maximizing the use of materials within the operation
- Reduction in costs associated disposal of waste materials by minimizing the amount of waste that must be disposed
- Reduction in potential liability associated with off-site waste disposal
- Reduction in effort and manpower needed to manage waste material

Waste minimization incorporates source reduction and material reuse, recycling and reclamation as ways of reducing the amount of material that ends up being treated as a waste material.

4.7.4 Universal Waste Management

The EPA promulgated the universal waste management regulations on May 11, 1995, that provide a regulatory framework that is less burdensome than the hazardous waste regulations to address certain widely generated waste materials. The intent of this program is to provide a streamlined regulatory process to promote the recycling of the universal waste materials where they otherwise would likely end up in municipal landfills. The waste materials covered by the original universal regulations included batteries, pesticides and thermostats. On July 6, 1999, EPA added hazardous waste lamps to the list of universal waste materials. On August 5, 2005, the EPA expanded the universal waste list further adding mercury-containing equipment.

The federal universal waste management regulations are codified in 40CFR Part 273. The regulations include management standards for four types of operators:

- Small quantity handlers of universal waste
- Large quantity handlers of universal waste
- Universal waste transporters
- Universal waste destination facilities

Because the universal waste management regulations are less stringent than the hazardous waste regulations, the state agencies have to adopt the regulations or develop state equivalent regulations for the universal waste management regulations to be effective in a state that has an authorized hazardous waste management program. States also may adopt only certain aspects of the universal waste management regulations and not implement the federal regulations in their entirety. For these reasons, aggregates operators must review the regulations for their states before implementing a universal waste management program.

Table 4.7 Universal Waste Handler and Hazardous Waste Generator Requirements

	SQHUW	LQHUW	CESQG	SQG	LQG
Quantity Limit	< 5,000 kg (§273.9)	>5,000 kg on site (§273.9)	< 100 kg < 1 kg acute (§261.5(a) and (e)	100 to 1,000 kg (§262.34(d)	> 1,000 kg or > 1 kg acute (Part 262 and §261.59e)
EPA Identification Number	Not required (§273.12)	Required (§273.32)	Not required (§261.5)	Required (§262.12)	Required (§262.12)
Accumulation Limit (kg)	< 5,000 kg (§273.9)	No limit	< 1,000 kg < 1 kg acute <100 kg spill residue from acute (§261.5(f)(2) and (g)(2)	< 6,000 kg (§262.34(d)(1)	No limit
Storage Time Limit	1 year, with extension available (§273.15)	1 year, with extension available (§273.35)	None (§261.5)	<180 days or < 270 days (§262.(d) and (e))	< 90 days § (§262.34(a))
Manifest Required	Not required (§273.19)	Not required, but must keep shipping records (§273.39)	Not required (§261.5)	Required (§262.20)	Required (§262.2))
Personnel Training	Basic training (§273.16)	Basic training geared toward employee responsibilities (§273.36)	Not required (§261.5)	Basic training (§262.34(d))	Full training as outlined in (§265.16 and 262.34(a))

The differences in the federal universal waste management requirements and the federal hazardous waste regulation requirements are listed in Table 4.7. As Table 4.7 illustrates, the universal waste management regulations are considerably less stringent than the regulatory requirements of the hazardous waste regulations for small and large quantity generators, while the differences between the universal waste regulatory requirements and the conditionally exempt small quantity generator requirements are not as significant.

In states where the universal waste regulations are being implemented, the aggregates operator is able to choose whether to handle the universal waste materials as universal waste and comply with these regulatory requirements or to continue to manage the material as hazardous waste and comply with the requirements based on the generator classification.

4.7.5 Waste Material Management at Aggregates Mining Operations

4.7.5.1 Mining Refuse and Overburden

Overburden is not normally considered to be a waste material but it still is subject to site specific management requirements as a condition of mine permit and/or mining regulations where applicable. Some site development materials such as wood waste and brush can fall under the solid waste classifications depending on how they are managed and the extent that applicable state and/or local regulations are applicable. The management techniques used for each of these materials varies significantly depending on the site characteristics, the amount of material generated and other site specific issues. In many cases, a significant amount of overburden from initial site development is used to build berms and for site grading. Regardless of how overburden is managed, control of stormwater runoff, fugitive dust emissions and security to prevent dumping from third parties of trash and debris must be established.

The following are examples of commonly generated materials from aggregates operations that if discarded could be considered waste material, depending on the federal and state waste management regulations. Some examples of common management techniques used by the aggregates industry to manage these materials and examples of waste minimization practices that may be employed are also provided.

4.7.5.2 Trash/Sanitary Waste

Aggregates operations generate common office type trash such as used paper, cardboard, plastic containers, bottles, cans, etc., as do other types of businesses. The common management method is to place this material in dumpsters provided by the local municipal trash service provider so that it can be collected and sent to a local or regional landfill for disposal.

Waste minimization techniques can be used including the use of recycling services where the facility personnel separate recyclables from trash. Common recyclables from office trash include paper, glass and aluminum cans.

4.7.5.3 Scrap Metal

The aggregates processing equipment contains a considerable amount of steel and this steel is subject to abrasion, erosion, corrosion and vibration fatigue that eventually results in equipment failure or need for substantial repair or reconstruction. These activities generate quantities of steel that must be managed, often referred to as scrap steel.

Waste minimization techniques that can be used by the aggregates operation start with designing and maintaining the equipment in a manner that extends it useful life. This includes repairing weak or thin areas in steel panels, resurfacing wear parts, lining chutes and hoppers with anti-wear material if feasible to protect the steel and other methods. The other practice commonly followed by the industry is to have the scrap steel managed by a scrap steel company so that it is recycled versus placing the material in a landfill.

4.7.5.4 Tires, Conveyor Belting and Rubberized Decking

Other equipment used in aggregates operations that is susceptible to significant wear includes equipment tires, conveyor belting and rubberized decking material. These materials are not hazardous waste when discarded but due to their volume and mass they are not materials that the industry normally likes to dispose of in a landfill. There is no standardized or common approach to managing these materials. The aggregates industry has dealt with these materials in many different ways over the years and is always looking for more economical options. Some examples of ways these materials are managed include the following:

- Use of the tires as a fuel and iron source for cement plants and other types of furnaces; as barriers for sports venues; in playgrounds; and in building artificial reefs; etc.
- Use of conveyor belting for walking surfaces in agricultural applications such as poultry farms, as a protective surface in processing equipment such as impact points for the aggregates in chutes.

Premature wear of these materials increase operating and maintenance costs associated with replacement of the tires, belting or screen deck materials. The most significant waste minimization technique is to operate and maintain the equipment to maximize the useful life of these items.

4.7.5.5 Used Oil and Oil filters

The aggregates industry utilizes an extensive fleet of mobile equipment to move material within the operation, to support the operations and to distribute the products. This equipment as well as the processing equipment uses various grades of lubricants such as oils and greases in the engines, gear boxes and other components of the equipment. This equipment also included oil filtration devices such as oil filters, to keep the lubricants free of impurities that would shorten the operating life of the equipment. These lubricants and filters must be disposed of properly and in compliance with the federal and state regulatory requirements. In some states such as California, these materials are treated as state specific hazardous waste.

The common management methods used by the industry for these materials include collection of the oil, lubricants and filters at the facility and storage in suitable containers and/or tanks pending pick-up by either a oil recycling firm or a waste management vendor. Some of the waste minimization methods used within the industry for these materials includes:

- Implementation of equipment maintenance and service programs that help extend the useful life of the lubricant by providing more efficient filtration to remove contaminants;
- Selection and use of the proper lubricants for the equipment being serviced;
- Filter crushing and draining processes to reduce the amount of oil in the filters when disposed;
- Use of the oil as fuel; and
- Sending the used oil and filters to a recycler instead of the materials being sent to disposal.

4.7.5.6 Antifreeze

Some of the equipment at aggregates operations use antifreeze compounds to protect the engines and cooling systems from freezing during the colder weather. Antifreeze must be managed properly and not released to the environment. The common management method for antifreeze is to have a reputable waste service company pick up the material so that it can be properly managed at an off-site location.

The waste minimization methods employed in the industry can include the use of extended life antifreeze so that the material lasts longer to reduce the amount of antifreeze that must be managed. In some cases, alternative "green" antifreeze products are used that are not as potentially harmful to the environment or animals. A third methods is to implement an effective equipment maintenance system that keeps track of the quality of the antifreeze and determines when it should be taken out of service.

4.7.5.7 Cleaning Solvents

Aggregates production sites often include co-located shops that service the mobile equipment fleet as well as the processing equipment. As part of the equipment servicing, the equipment and parts must be cleaned and degreased so they can be properly inspected, repaired and replaced. The process of cleaning parts commonly involves the use of parts washers, that in some cases use various forms of solvents to provide the cleaning and grease cutting ability. Depending on the type of solvent and its flash point, the solvents used for parts washing may be classified as either federal or state specific hazardous waste. The common management technique for these solvents is to have the solvent supplier pickup the used solvent as a turn-key service when fresh solvent is provided. In cases where this service is not used, the aggregates operator must determine the proper management method either involving off-site disposal of the material or off-site recycling and recovery of the solvent. The process of cleaning larger pieces of equipment generally involves steam cleaning in a dedicated area where the resulting wash water can be collected for recycle back through the system or handled as a waste stream per local regulations. As a waste it may be picked up and disposed of by a licensed vendor or in some cases run through an oil/water separator and discharged (with a permit) through the facilities process water discharge if authorized by permit. Some states distinguish between a cold water wash to remove earth from equipment and the wash using a steam cleaner when it comes to managing the wash water.

The waste minimization methods employed in the industry can include the following:

- Careful management of the degreasing system to extend the useful life of the solvent, including controlling the pick-up frequency for the used solvent;
- Use of non-hazardous solvent blends that will not require treatment as a hazardous waste;
- Use of industrial dishwasher style parts washers that use detergent and high pressure water instead of solvents;
- Pre-washing of equipment to remove dirt and mud so that the solvent does not become contaminated by the dirt and mud when it is used; and
- Providing the used solvent to a facility that will purify the solvent and prepare it for reuse instead of sending the material directly to a disposal facility.

4.7.5.8 Petroleum Impacts Media (Soils, Rags, Absorbent Pads)

In the course of operating, servicing and repairing equipment there will be petroleum contaminated media generated that requires disposal. This can include greasy rags, oil absorbents, oil spill response equipment and occasionally oil contaminated aggregates media such as rock fines and soil. These materials are generated as part of the operation's proactive response to small drips, leaks and other spills that occur associated with the equipment and transfer of petroleum products. The common management technique for these materials is to collect them and place them in a suitable container where they can be stored until the container is full; at which point the facility arranges for the container to be picked up by the waste service provider.

The waste minimization methods employed in the industry can include:

- Following equipment maintenance and petroleum product transfer procedures that minimize the risk of spills and leaks of petroleum substances;
- The use of impermeable containment structures for petroleum storage tanks and concrete pads where feasible in areas where equipment is fueled or serviced; and
- Ensuring that any spills of petroleum substances are contained and cleaned up quickly to minimize the risk of the spill spreading and contaminating a larger area.

4.7.5.9 Batteries, Light Bulbs and Electronic Equipment

Aggregates operations generate materials that are classified as universal waste including batteries, light bulbs, mercury containing equipment (switches, etc.) and also electronic equipment such as computers, monitors and other items that may contain small amounts of hazardous materials such as lead, mercury and other materials. The management methods employed by the industry vary widely for these materials, in some cases aggregates operators handle these materials under the solid and hazardous waste regulations, while others handle according to the universal waste regulations.

The waste minimization methods employed in the industry can include:

- Collection of the materials and transfer to waste service providers who recover the metals from the equipment prior to disposal, thus reducing the amount of hazardous substances placed in the landfills; and
- Electronic equipment such as computers, monitors and other items can be provided to a third party for continued use such as to school systems.

4.7.5.10 Paint, Spray Cans and Other Miscellaneous Containerized Materials

The aggregates industry uses paint and other various substances that are provided in containers and spray cans that must be managed properly and in accordance with the federal and state waste management regulations. The most effective management and waste minimization techniques for these materials are:

- In the procurement process, select products for use that contain less hazardous constituents or lower concentrations of hazardous constituents that will still provide the results needed from the product; and
- Ensure that all of the product is used for its intended purpose and the containers are empty prior to disposal.

The containers must then be disposed of according to the applicable requirements under the federal and state waste management regulations.

4.7.6 Liability Associated with Waste Management

The aggregates industry's waste management practices are critical to not only controlling operating cost and reducing the amount of waste disposed into the local and regional landfills, but also to preventing the owner and operator of the aggregates operation from being held liable for investigation, response and cleanup of contaminated properties. The federal hazardous waste regulations include a legal concept referred to as "cradle to grave" liability. This essentially means that the original generator of waste material is responsible for management of that waste material throughout the waste management process to the ultimate disposal of the waste material. This potential generator and owner/operator liability is further defined under the federal Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA), commonly referred to as "Superfund," that establishes programs and resources to respond and address contamination incidents such as those arising from soil, sediment or groundwater contamination from waste management practices. The financial burden of being named as a potentially responsible party (PRP) at a CERCLA site can be significant depending on the extent of the contamination and the specifics of the amounts and types of waste materials that were sent to the site for disposal.

Some ways that can help reduce the potential for future CERCLA liability include the following as examples, this is not a comprehensive list nor is it intended to provide legal guidance:

- Apply waste minimization techniques to reduce the amounts and toxicities of waste materials sent off-site for disposal
- Understand where the materials go when they leave the aggregates facility. Establish business relationships with waste service providers who open about how the materials are managed and helpful in addressing any potential concerns
- Ensure that there are written legal contracts with the waste service providers that provide for indemnity and insurance coverage from the waste service provider to the aggregates operator/owner that cover potential liabilities that may arise
- Periodically review the financial condition of the waste service provider and also the compliance status of the sites the materials are managed at and disposed
- In the event a notice is received from the government or other party concerning CERCLA, state equivalent or third party liability, engage legal counsel promptly to provide advice and direction

4.8 Management of Petroleum Substances and Other Chemicals

The aggregates industry uses various petroleum and chemical products throughout the aggregates production process. The industry follows applicable regulatory requirements and best management practices to ensure that these substances are stored, handled and used in a manner that protects people and the environment from any adverse impacts associated with the use of these materials.

In addition, the aggregates industry in compliance with MSHA requirements and other applicable regulatory standards maintains Emergency Response Plans and in some cases separate Spill Response Plans. These plans document the procedures followed in the event there is a spill, fire or other incident that has the potential to release a petroleum substance or other chemical to the environment or expose people to a hazard associated with the material. The industry trains employees on the emergency and spill response procedures and in many locations conduct periodic practice drills to ensure that the employees and response authorities understand how to react and respond in the event of a true emergency.

Petroleum substances and other chemicals are handled with care and stored in locations in a manner to both protect the integrity of the storage container and the materials in order to minimize the risk of a spill or release to the environment. Operations are required to have Material Safety Data Sheets (MSDS) available for these materials under the MSHA Hazcom regulation, which provides information on the hazards of the materials being used so precautions in handling, storage and use can be implemented.

The aggregates industry also is mindful of the need to control the use of materials that contain potentially toxic or hazardous components or chemicals that are persistent and biologically accumulative to the extent possible. By doing so, any spill or release if it were to occur would not have as significant an impact on the environment. Generally, the industry does not use many materials that are extremely hazardous or extremely toxic and the chemicals with the most significant risks tend to be the petroleum substances such as gasoline and diesel fuel, which are subject to strict regulatory requirements and management standards as discussed below. As new information or concerns arise regarding materials used by the industry, the aggregates companies normally have enough flexibility to evaluate the potential to go to materials that do not have the same level of environmental or human health concern. In situations where the material is critical to the aggregates production process, the industry will take steps to enhance the controls and management standards followed in relation to the use of the material to reduce the risk of human exposure, environmental harm and other areas of concern.

Table 4.8 Petroleum and Chemical Products Used by Industry

Material	Common Uses
• Diesel, gasoline, natural gas, propane, etc.	• Fuel for mobile and stationary equipment
• Oils, greases and other lubricants	• Provide lubrication to equipment
• Antifreeze, brake and power steering fluids	• Used to service equipment
• Explosives including ANFO and others	• Used in mining process
• Cleaning agents such as petroleum, citrus and detergent based solvents	• Used to clean equipment and parts
• Paints and other coatings	• Used to protect equipment from corrosion
• Solid absorbent agents	• Used in spill response
• Surfactants, biocides and algaecides, etc.	• Used to treat water
• Various acids or bases	• Used to adjust pH of waste water
• Welding rods, sheet metal and gas cylinders	• Used in equipment welding
• Fly ash, cement, asphalt cement, concrete additives (retarders, accelerators, etc)	• May be present on site associated with downstream business or used in recycled products

The care and attention placed on proper management of these materials minimizes the risk associated with their use. Some of the petroleum and chemical products commonly used by aggregates operations are listed in Table 4.8.

The following sections provide information on management techniques and regulatory requirements associated with the use of petroleum substances and other chemicals at aggregates production operations.

4.8.1 Regulatory Areas

There are a number of federal regulatory requirements that apply to the industry related to the management, use and storage of petroleum substances and other chemicals. The following is a brief overview of the applicable federal requirements. This overview is not intended to be a comprehensive list as each operator must establish their compliance program based on the applicable requirements of the Spill Prevention, Control and Countermeasure (SPCC)regulations.

4.8.1.1 Hazardous Communication Rules

The MSHA and OSHA regulations require facilities covered by their standards to implement a hazard communication program. The determination of whether a specific operation is subject to MSHA or OSHA jurisdiction is necessary to ensure that the operation is applying the correct standards. The major components of the hazardous communication rules include identification of chemicals being used at the facility, requirements to either prepare or obtain MSDS for these chemicals and the implementation of an employee training program designed to communicate the hazards associated with each chemical to the employees. The MSHA Hazard Communication rule is located at 30CFR Part 47 and the OSHA Hazard Communication rule is located at 29CFR Part 1910.1200. These regulations contain many requirements beyond what is covered in this paragraph. The aggregates operators must review the applicable regulations in detail to ensure that all applicable requirements are identified.

4.8.1.2 Emergency Planning and Community Right to Know Rules

The Emergency Planning and Community Right-to-Know (EPCRA) regulations were established following a series of chemical plant accidents that exposed the vulnerability of the public to chemical releases, fires and other disasters that can occur with little advance warning. The sections of these regulations and the requirements associated with each section are summarized in Table 4.9.

The applicability of the various EPCRA regulations to aggregates operations must be determined on a facility specific basis and must be re-evaluated each year as changes either with the facility, with the chemicals used or with the regulations will impact this determination.

Table 4.9 EPCRA Sections and Major Requirements Overview

Regulatory Section	Primary Requirement
Section 302 Emergency Planning (40 CFR 355.30)	A facility that has quantities of hazardous substances at or above threshold values listed in 40 CFR Part 355 must notify the State Emergency Planning Commission (SEPC) that they are subject to the requirements. The facility must designate a person as emergency response coordinator to participate on the Local Emergency Planning Commission (LEPC).
Section 304 Emergency Release Notification (40 CFR 355.40)	A facility that produces, uses or stores a hazardous chemical must notify the SEPC/ LEPC if there is a release of a listed hazardous or extremely hazardous chemical exceeding the reportable quantity listed in 40 CFR 355, Appendix A and B. Releases of CERCLA listed hazardous substances must also be reported to the National Response Center (NRC) and transportation related releases must also be reported to state and local authorities.
	A facility that produces, uses or stores a hazardous chemical must notify the SEPC/ LEPC if there is a release of a listed hazardous or extremely hazardous chemical exceeding the reportable quantity listed in 40 CFR 355, Appendix A and B. Releases of CERCLA listed hazardous substances must also be reported to the National Response Center (NRC) and transportation related releases must also be reported to State and Local authorities.
Section 311 Community Right-to-Know Requirements (40 CFR 370.21)	Facilities required by OSHA to prepare MSDSs are required to submit copies of the MSDSs or corresponding lists to the SEPC/LEPC and local fire department with jurisdiction for the site if the applicability criteria are met. A list can be provided in lieu of the MSDS sheets but the MSDS sheets must be provided within 30 days if requested.
Section 312 Inventory Reporting (40 CFR 370.25, 370.40, 370.41)	Facilities required by OSHA's Hazard Communication Standard to prepare or have MSDS may be required to submit annual emergency and hazardous chemical inventory forms (Tier I or Tier II) to the SEPC/LEPC and fire department if the applicability criteria are met. The deadline for reporting is March 1 of each year.
Section 313 Toxic Chemical Release Reporting (40 CFR Part 372)	Facilities that meet the applicability criteria are required to submit toxic chemical release reports (Form R) for each toxic chemical manufactured, processed or otherwise used above threshold values by July 1 of each year.

4.8.1.3 Spill Prevention, Control and Countermeasure Regulations

The management of materials classified as oil is regulated at the federal level under the SPCC regulations that are codified within 40 CFR Part 112. The regulations apply to facilities that have quantities of oil above the applicability thresholds in the rule. The regulations define oil to include "any kind or in any form including, but not limited to, petroleum, fuel oil, sludge, oil refuse and oil mixed with wastes other than dredged spoil." EPA interprets this definition to include crude oil, petroleum and petroleum-refined products, as well as non-petroleum oils such as vegetable and animal oils. The SPCC regulations affect most aggregates production operations due to the amounts of petroleum products used and stored in tanks and containers (the petroleum products include diesel, gasoline, oils, greases and other materials that vary by site). The major regulatory sections of the SPCC regulations that impact aggregates operations are provided in Table 4.10.

The list is not meant to be a comprehensive compliance guideline, but instead intended to illustrate the major areas that affect aggregates operations.

Table 4.10 SPCC Regulatory Sections Primarily of Interest to Aggregates Industry

Regulatory Section	Regulatory Requirement(s)
40 CFR Part 112 Subpart A	General requirements, applicability and definitions
Section 112.1	Applicability
Section 112.2	Definitions
Section 112.3	Requirements to prepare and implement an SPCC plan
Section 112.4	Amendment of SPCC plan by Regional Administrator
Section 112.5	Amendment of SPCC plan by owners or operators
Section 112.6	Qualified facility plan requirements
Section 112.7	General requirements for SPCC plans
40 CFR Part 112 Subpart B	Requirements for petroleum oil and non-petroleum oils
Section 112.8	Spill Prevention, Control and Countermeasure Plan requirements for onshore facilities (excluding production facilities).
40 CFR Part 112 Subpart D	Response requirements

Some of the major requirements of the SPCC regulations and common approaches followed by the industry to address the requirements are provided in the following sections. This is not a comprehensive list and is provided for illustration purposes, aggregates operators must review the SPCC regulations in detail when establishing a compliance program to ensure that all applicable requirements are met.

4.8.1.3.1 Requirement to Prepare and Maintain SPCC Plans

The SPCC rules require facilities subject to the rule to prepare and maintain SPCC plans that meet the requirements of the regulations. The contents of the plans must comply with the requirements of regulations and the plans must be approved by management and certified by a professional engineer. The plans are required to be updated whenever facility conditions, equipment or other changes occur to ensure that the information in the plan is accurate and current. Otherwise, the plans must be updated and recertified at least every five years.

4.8.1.3.2 General Containment Requirements

The SPCC rules require facilities to implement measures that prevent the release of oil, but in the event a spill occurs the regulations require facilities to have implemented general containment measures to prevent the spill from being discharged to navigable waters. The general containment measures can be active or passive, and the regulations provide flexibility in the specific measures a facility implements. Some examples of equipment and areas within an aggregates production operation that require implementation of general containment measures include fuel and petroleum product off-loading, dispensing areas and systems, crusher lube systems, mobile fuel and other service vehicles containing oils and other oil filled equipment. The industry uses the following measures as means of satisfying the general containment requirements. These are examples and there are other measures used that are not listed and each of these measure may not be used at any specific operation:

- Placing parked mobile equipment containing oils in locations where any spill will collect in the immediate area and not drain away and using spill response measures to collect the spilled material.
- Designing plant process areas so they are sloped to drain to a location where the oil is not released, such as to the quarry pit, settling ponds, catchment swales or other features that provide containment of the spilled oil that is sufficient to prevent a release until the spill can be addressed.
- Designing equipment fueling areas and oil product transfer areas so that any spills drain back to a containment system with adequate capacity to contain the spilled oil until it can be collected.
- Implementation of spill response measures to respond and address any spills that occur before the material can reach navigable waters.

4.8.1.3.3 Bulk Container Requirements

The SPCC rules require all containers and bulk tanks that have a storage capacity of 55 gallons or more to be provided with specific secondary containment measures that are designed to contain spill oil without any release to the environment for a period of time sufficient to allow response to the spill. The containment system must be designed and constructed in a manner to prevent a release from the floor and walls and any associated valves or drains must not allow a release.

The regulations allow the use of double-walled vessels as a means of satisfying the secondary containment requirements. In the event that an external containment structure is used the capacity of the containment structure must be sufficient to contain the contents of the largest vessel contained within, while providing sufficient freeboard to contain a 24-hour 25-year storm event.

Bulk containers are also required to be equipped with high level alarm and response systems and liquid level detection systems. Bulk tanks are required to meet engineered best management practices designed to minimize the risk of a spill.

The regulations also include requirements for performing integrity testing of bulk containers to ensure that the containers have the necessary structural integrity to store the oil without risk of vessel failure due to corrosion, damage or other integrity issues.

4.8.1.3.4 Site Security Measures

The SPCC regulations require sites to provide adequate security measures to prevent unauthorized access to oil storage and dispensing equipment and to provide lighting as needed to provide adequate illumination of the area. The regulations provide flexibility to the operators in decided what is needed to satisfy these requirements. The industry has taken a variety of different approaches to providing security, which include:

- Use of security guards and 24-hour monitored camera and alarm systems
- The use of fencing to control access to the areas where oil is stored, transferred and used. The layout of the fencing varies significantly from fencing of entire operations to only fencing the immediate areas where oil is managed
- The use of locked caps, valves and control systems for material transfer pumping and dispensing equipment
- Locating equipment inside the property within the quarry pit where access is limited

4.8.1.3.5 Loading and Unloading Systems

The SPCC regulations require containment to prevent the release of oil associated with leaks and spills from loading and unloading systems. It is common for an aggregates production operation to have bulk tanks that store fuel and oil that are associated with material transfer during loading of the tanks and dispensing of the fuels and oils. The SPCC regulations include more stringent requirements for facilities that include "loading racks" such as a requirement for full secondary containment versus general containment for sites that do not have loading racks. The industry has taken a variety of approaches to addressing the SPCC requirements regarding loading and unloading systems, including the following:

- Providing impervious pads and containment curbing in areas where loading and unloading operations occur
- Implementing material transfer procedures and guidelines that provide clear instruction on the steps to take to prevent a spill from occurring
- Consolidating fuel and oil storage areas so that the transfer activities are concentrated in a limited number of areas
- Incorporating advanced monitoring systems and alarm equipment, break away hoses, backflow valves in dispensing lines, etc. that reduce the risk of a spill
- Coordination with site response personnel regarding planned material transfer operations to facilitate rapid response in case of a spill
- Ensuring that material transfer areas drain to containment structures such as pits, impoundments, sumps, etc. where the oil is contained until it can be recovered

4.8.1.3.6 Facility Inspection Requirements

The SPCC regulations mandate inspections of oil-containing equipment, bulk storage vessels and other areas within an aggregates production operation to ensure that equipment is not leaking, containment structures are sound, that there is no evidence of petroleum or oil spillage and that containment structures are dry and free of debris and other materials that could affect their capacity to contain a spill. The specific inspection requirements applicable to an aggregates production operation must be determined by review of the SPCC regulations and the inspection program and results must be documented within the SPCC plan.

4.8.1.3.7 Personnel Training Requirements

The SPCC regulations mandate training of new employees whose job involves the handling or use of oils or the operation or maintenance of oil containing equipment at the start of their job and requires annual refresher training on SPCC requirements for these types of employees, referred to as "oil-handling" employees.

The contents of this training and records of the completion of the training must be retained to demonstrate compliance with the requirements of the regulations.

4.8.1.3.8 Spill Response and Countermeasure Requirements

The SPCC plan must include information on the operations spill response and countermeasures procedures that are to be implemented in response to an oil spill that threatens navigable waters. The facility must ensure that the necessary response equipment is available and assessable for use in the event of a spill. The type and amount of spill response equipment that is required is dependent on the types of spills that are reasonably anticipated to have the potential to occur. Some examples of spill response practices and countermeasure equipment stored on-site at aggregates production operations are as follows:

- Identify the oil spill scenarios that are potential possibilities at the site based on locations of oil containing equipment and containers, locations where oil transfers occur, volumes of oil contained, etc. and from that information evaluate the quantity and location of spill response equipment to deploy at each site.
- Develop spill response plan specific to each operation that references response equipment and materials available for use, personnel to contact, third party response contractor contact information, agency contact information, etc.
- Review oil spill response plan with plant personnel and establish and assign responsibility for response activities.
- Meet with local emergency response authorities and review materials stored on-site and discuss response needs and coordination procedures.
- Conduct periodic response drills internally and if possible include the local response authority in the process.
- Periodically inspect spill response and countermeasures equipment and materials to ensure it is located where it is needed, that it is still in sound condition and sufficient quantity to provide response capability.

4.9 Environmental Management Systems

4.9.1 Introduction

Unlike environmental protection programs established by regulation, an Environmental Management System (EMS) is not a legal requirement and is not prescriptive in nature. An EMS is comprised of procedures and policies to manage potential impacts to the environment and the health and welfare of individuals.

An EMS can be a valuable tool for your business to track and improve environmental performance. While each EMS is specifically tailored to the business or facility which develops it, all are based on the following framework:

- **Plan:** Identify the environmental goals.
- **Do:** Develop and implement procedures for achieving those goals.
- **Check:** Verify that the procedures are successful in achieving the goals.
- **Act:** Modify the procedures as necessary to continually improve them.

EMS proponents find the use of an EMS program provides environmental and economic benefits for both their facility operation and the public. The range of benefits identified by EMS users include increased operational efficiency, improved compliance performance, reduced liability and improved relationships with customers, suppliers and the community.

4.9.2 EMS Objectives and Standards

4.9.2.1 Objectives

4.9.2.1.1 Compliance

Compliance with applicable environmental regulations is an EMS core objective. While an EMS will not guarantee compliance with all applicable regulations, it is intended to enable a business to approach its environmental compliance obligations in an organized manner. An EMS helps the business track environmental compliance and prompts it to create procedures for assessing and meeting compliance obligations. Through these procedures, the company can more easily manage its compliance. A systematic program also may help reduce environmental impacts across a variety of media, thus achieving pollution reduction more efficiently than focusing on one medium at a time.

4.9.2.1.2 Liability Reduction

An EMS can help reduce exposure to liability by reducing the incidence of environmental noncompliance. Furthermore, when there is environmental noncompliance, enforcement bodies may look favorably upon a facility that has made the effort to implement an EMS when it comes time to determine the penalty. As is discussed more fully in § 4.9.4.2 below, EPA may not impose gravity-based noncompliance penalties under certain circumstances fostered by EMSs. In addition, the implementation of an EMS can help to avoid a pattern of noncompliance by integrating operation-wide improvements reflecting the policy, training and auditing functions of the program.

An EMS also can help a business avoid other liability beyond that arising from enforcement for noncompliance. The process of assessing environmental performance on a holistic basis can cause plant managers to become aware of and remedy other possible sources of liability. For example, an EMS can facilitate the identification and correction of operating processes that impact neighboring properties before they become larger problems. When a facility improves its noise and dust control practices, it reduces its exposure to nuisance claims by abutting property owners, as well as fostering better community relationships as a whole. Liability reduction in the broad sense can take many forms and maintaining good relationships with other stakeholders, in part through an effective EMS, can mean real savings in the costs of securing permits and approvals by reducing objections to a facility operation. EMS efforts that lead to improvement in worker safety may reduce workers' compensation claims. By systematically evaluating potential environmental impacts, an EMS can help reduce liability exposure far beyond that which directly results from environmental noncompliance.

4.9.2.1.3 Performance Improvement

A good EMS will do more than foster compliance with environmental laws and will identify means for the business to improve its environmental and overall performance. For example, an EMS can help identify wasted resources like water and energy, eliminate waste or inefficiency and thereby reduce input costs. An EMS also may prompt the business to identify and adopt improved technology that provides benefits in both productivity and environmental benefits. By focusing on overall performance rather than just compliance, an EMS can have real financial benefits.

4.9.2.1.4 Stakeholder Relationships

A well-crafted EMS shows that the business is serious about evaluating and improving upon its environmental performance. This can help improve relationships with a variety of stakeholders. If the EMS has robust procedures in place for minimizing impacts to neighboring properties (e.g., noise and dust, surface water runoff) it may ease community concerns about the facility and foster a more positive relationship. Similarly, a commitment to environmental issues may help the business attract and retain customers seeking to do business with those who demonstrate a commitment to improved environmental performance, like those in the green building field. Finally, shareholders may demand increased attention to environmental issues and a good EMS may foster a company profile attractive to investors or lenders that see it as a business enhancement tool.

4.9.2.2 Standards

4.9.2.2.1 EMS Models and Programs

While all EMS models are based on the Plan, Do, Check, Act framework, there are several different models that your business can use as a framework for developing an EMS. Some examples include:

- **ISO 14001:** This may be the most popular model used to create an EMS program. It was developed by the International Organization for Standardization (ISO), the same organization that developed the popular ISO 9000 Quality Assurance system. ISO 14001:2004, Environmental Management Systems – Requirements with Guidance for Use is the central document in the ISO 14000 series and it sets forth the basic requirements for an EMS. A company may elect but is not required to submit its EMS to an audit in order to secure an independent certification that it is meeting all the requirements that ISO 14001 sets forth. Other documents in the ISO 14000 series provide additional details and implementation guidance. For example, ISO 14004:2004, Environmental Management Systems – General Guidelines on Principles, Systems and Support Techniques builds upon the same requirements set forth in ISO 14001 with "General Guidance" and "Practical Help" sections to aid companies as they implement the ISO 14001 requirements. If your business already uses ISO 9000, you may find quite a bit of overlap with ISO 14001. ISO 14001 can be a useful starting point for developing an EMS, even if the business has no intention of completing the formal ISO 14001 certification process.
- **European Eco-Management and Audit Scheme (EMAS):** Developed in the European Union, it can be tailored to all sectors.
- **Sector-Specific Templates:** A variety of industries have developed EMS templates that more specifically fit their needs. For example, the International Council of Chemical Associations developed the Responsible Care model to address the specific needs of the chemicals industry. See Section 6.4.1.1 for further detail on a sector-specific template developed by NSSGA.

4.9.2.2.2 Corporate Commitment

In order for an EMS to be effective, it needs to be embraced by all constituencies in the business. Without top corporate support, an EMS program will not obtain the financial or staffing resources required for success. Corporate leadership has several responsibilities relative to the EMS. They must identify the organization's priorities, develop its corporate policy and identify the key individuals and teams to take the lead in the EMS efforts. It is also important for other groups in a business to participate in the EMS process. Without commitment from all types of workers, the EMS will be impossible to implement. Collaboration and commitment to the EMS will be enhanced where the EMS team includes members from a variety of levels and job functions.

4.9.2.2.3 Corporate Policy

The corporate policy is the cornerstone of an EMS, "the framework for setting and reviewing environmental objectives and targets." For example, in the ISO 14001 system the corporate policy reflects three commitments:

- **Commitment to continual improvement:** In undertaking the EMS the company must strive to continually improve its environmental performance and also to continually improve the EMS itself.
- **Commitment to prevention of pollution:** The organization should strive to prevent pollution from occurring, rather than merely abating it once it already has occurred.
- **Commitment to comply with applicable environmental laws and regulations:** The organization need not be in perfect compliance to have a workable EMS. The organization should, however, identify applicable laws, evaluate the facility's compliance status and formulate a strategy for correcting noncompliance issues.

If possible, the easiest way to develop a policy that all employees understand and support may be to start with the company's existing environmental policy, however simple, as a basis of an EMS program.

4.9.2.2.4 Responsibility Manager

The responsibility manager is the person who leads the organization's EMS team and serves as the liaison between the team and upper management. While the size and composition of the EMS team can vary widely according to the needs of that particular business, it is advisable to involve a diverse array of personnel from a variety of job functions. Each person will be able to use their on-the-job experience to formulate an EMS that is integrated with existing company culture and practice. Furthermore, it likely will be easier to raise awareness and gain acceptance of the EMS if all groups in a company can see that the EMS team includes representatives from throughout the company who will be aware of the functions, concerns and perspectives of all groups.

4.9.3 EMS Elements

4.9.3.1 Environmental Compliance

While having an EMS does not guarantee environmental compliance, evaluation of current compliance and progress toward improved compliance are important features of any EMS. The EMS should include a procedure for evaluating which environmental laws and regulations apply to the business' operations and to ensure that compliance can be maintained even under changing standards. The EMS also should include a procedure for monitoring current compliance. Despite the EMS team's best efforts, there may be instances where applicable standards are unknown, misunderstood or actively disregarded by particular employees. There should be both education and accountability procedures in place to address deviation from applicable standards or the EMS. Finally, the EMS should include procedures for documenting and resolving nonconformities with the EMS and noncompliance with applicable regulations. By evaluating conformity with the EMS and compliance with regulations in a systematic way, the business is better positioned to reduce noncompliance including repeat incidents, improve training and maintain the effectiveness of the EMS.

4.9.3.2 Standard Procedures and Documentation

EMS models do not typically require that the business evaluate and improve its environmental performance by application of a specifically mandated approach. Instead, they provide a framework for the business to use established procedures for fulfilling its environmental goals. For example, under ISO 14001:

- The business must have a procedure for evaluating which environmental laws and regulations apply and must have access to those regulations.
- The business must have a procedure for communicating internally about environmentally significant aspects of the business and receiving input from outside stakeholders.
- The business must have a procedure to identify the potential causes of accidents and emergencies.

There are two important classes of documents related to an EMS. The first, "EMS documentation" describes the EMS policy and procedures and provides a set of guidelines or instructions for implementing the EMS. This ensures that all employees are "on the same page" and understand what is expected. The second, "EMS records" allows the business to track what actually has occurred and verify that the EMS is being followed. Organized records also improve operating efficiency, save time and money and help demonstrate effective environmental management in the event of an investigation by a regulatory body.

4.9.3.3 Training

ISO 14001 requires that facility personnel be made aware of the EMS, that they are competent to handle the environmental issues they encounter and that they receive appropriate training on environmental issues. There may be opportunities to integrate EMS training with existing health and safety training. Training should be provided to both new and existing employees. Through the training process the EMS team also can gain valuable insight on how to improve environmental performance in the future. Various job functions interact with the environment in different ways, so these employees may offer valuable perspective on how to improve the business' environmental performance. Increased awareness cultivated by a sound program can give a practical perspective needed for effective problem-solving. The most effective training programs will allow for dialog between the trainers and trainees.

4.9.4 Self-Auditing and Disclosure

4.9.4.1 Self-Auditing

Through self-auditing, a company can determine how well it is living up to the goals of its EMS. The EMS documentation should include internal auditing procedures. The audits should be performed by people with the appropriate expertise but who are not directly connected to the operations being audited. The audit should assess both compliance with applicable environmental laws and conformity to the procedures outlined in the EMS. For every instance of noncompliance, the audit should investigate the root cause of the problem. For example, did a spill occur because of human error, equipment malfunction, lack of routine inspections or environmental factors? Naturally, a combination of factors may be implicated. As the company strives to prevent the issue from occurring in the future, it must know what specific problems or contributing factors to address.

An audit would involve both the review of records and the physical inspection of facilities. The exact features to inspect and records to review will depend on the facility in question and the environmental impacts of its operations. For example, an audit team evaluating performance with respect to stormwater management would likely review (among other documents) NPDES permits, the facility's Stormwater Pollution Prevention Plan, training records, discharge monitoring reports, the local sewer ordinance and any recent notices of violation. The audit team would likely physically inspect (among other features) discharge outfall pipes, parking lot drains, silt fences and sediment basins. In its environmental audit report, the audit team should present current conditions and suggested improvements.

An audit of facility operations can lead to the discovery of environmental violations or employee misconduct, or necessitate the reporting of violations or other interaction with environmental agencies. As the EMS team develops its audit procedures and when the team prepares to conduct an audit, especially the first EMS program audit, it would be wise to consult with the company's legal department or outside legal counsel. As discussed below in § 4.9.4.3, procedures may be available to protect the audit report, documents in draft form, audit notes or certain other documentation from disclosure to third parties under attorney-client privilege. In addition, with guidance from legal counsel, the audit team can draft its report in a manner that avoids unnecessary unfounded legal conclusions or errors in analysis that might be used by others for unanticipated purposes. Finally, it is wise to develop and have in place a plan for how to handle reporting requirements and correcting discovered violations.

4.9.4.2 Agency Policies

Agencies often look favorably upon businesses which self-report and promptly correct environmental noncompliance. In order to encourage the voluntary discovery and disclosure of non-compliance, EPA has adopted a policy of treating self-discovered noncompliance less severely if certain conditions are met. Specifically, EPA will forgo gravity based penalties (i.e., the portion of the calculated penalty based on the severity of noncompliance) when:

- The violation was discovered through an environmental audit or a compliance management system such as an EMS;
- The violation was discovered through voluntary monitoring (rather than monitoring required, for example, by an air discharge permit or consent decree);
- The company discloses the violation to EPA within 21 days of its discovery;
- The discovery did not occur in connection with a lawsuit or government investigation;

- The company corrects the problem within 60 days of discovery and remediates any environmental harm that may have resulted;
- The company agrees in writing to take steps to prevent a recurrence of the violation;
- The same violation has not occurred within the past three years at the same facility;
- The violation did not result in serious actual harm or present an imminent and substantial endangerment, to human health or the environment and it did not violate the specific terms of any judicial or administrative order or consent agreement; and
- The company cooperates with EPA and provides requested information.

When all of the above conditions are met except that the discovery was not made through an environmental audit or EMS, the gravity-based penalty will be reduced by 75 percent.[71] Furthermore, there can be a fine line between environmental enforcement actions taking a civil or criminal enforcement path. Enforcement authorities are more inclined to pursue administrative or civil enforcement rather than criminal prosecution when the forthrightness of the facility operators is reflected by their making a voluntary disclosure as outlined above.

Similarly, OSHA also has adopted policies to encourage self-audits. Specifically, OSHA will not issue a citation for noncompliance discovered as a result of a voluntary self-audit if the employer has corrected the condition prior to the initiation of an OSHA inspection (or the occurrence of an accident) and has taken appropriate steps to prevent a recurrence of the violation.[72] The MSHA does not have an analogous policy as of this writing. In 2010, the House Committee on Education and Labor urged MSHA to adopt a policy similar to that of OSHA.[73]

In most instances, the DOJ has substantial discretion to determine whether to criminally prosecute environmental violations. In an effort to encourage self-auditing and self-reporting, DOJ put forth factors that it uses in determining whether to criminally prosecute environmental violations. While the specific circumstances must be evaluated for each case, the following are factors that would be considerations in a DOJ determination of whether to pursue criminal enforcement:

- Whether there was voluntary, timely and complete disclosure of the violation;
- Whether the company cooperates with the authorities;
- The existence and scope of an EMS or other compliance program, whether it was adopted in good faith and in a timely manner and whether it provides sufficient measures to identify and prevent future noncompliance;
- Whether the noncompliance was systematic or pervasive, including "the number and level of employees participating in the unlawful activities and the obviousness, seriousness, duration, history and frequency of noncompliance";
- Whether the company takes disciplinary action against employees who violate environmental compliance policies; and
- The promptness and completeness of any action taken to remove the source of the noncompliance, mitigate the consequences of the noncompliance and prevent the noncompliance from occurring in the future.[74]

As the above agency policies indicate, agencies look favorably upon companies that establish credible compliance assurance programs, discover their own compliance problems and take the appropriate steps to address noncompliance in a timely manner. Importantly, self-auditing can be a positive factor in the eyes of reviewing agency personnel as well as assisting environmental managers to discover small problems before they grow into large problems.

4.9.4.3 Confidentiality and the Attorney-Client Privilege

Communications between a lawyer and a client, when made for the purpose of providing legal advice, are protected from compelled disclosure in most instances by the attorney-client privilege. In order for the attorney to render appropriate legal advice, the client must be confident that they may confidentially disclose all relevant facts without the risk that those facts will be discovered by others. The application of the attorney-client privilege to specific types of documents or information and the detailed procedures for effective use of the privilege is beyond the scope of this discussion. However, environmental managers should make a point to discuss these issues with company attorneys in the context of their EMS efforts.

Federal agencies do not, as a matter of practice, seek out environmental audit reports to discover noncompliance. Instead, they rely upon reporting incentives discussed in § 4.9.4.3. State laws vary widely and some specifically protect the confidentiality of environmental audit reports. In Oregon, for example, environmental audit reports are "privileged and shall not be admissible as evidence in any civil or administrative proceeding" except under certain specified circumstances.[75]

4.9.5 EMS Regulatory Issues

Since 2004, EPA has been evaluating whether and how EMSs should be integrated into the regulatory structure. EPA stresses that while EMSs are encouraged for all organizations, they should not be mandated. In order for an EMS to be effective it must be tailored to the business's goals and current practices and an EMS micromanaged by EPA may not be as effective as one more focused on the needs of the individual business. EPA has, however, begun to evaluate the extent to which performance based standards can replace EPA standards. EPA has also begun to evaluate how cross-media tradeoffs (such as better dust control with higher water usage) can be integrated into permitting programs, which focus on one medium at a time.

While EPA does not mandate the use of EMS generally, it may require the development of an EMS as part of an administrative settlement following noncompliance. As discussed above in § 4.9.4.2, EPA views the EMS process as an effective way to manage environmental compliance and avoid future noncompliance. Specifically, EPA supports incorporating the development of an EMS into administrative settlement as a means of addressing the root cause of the violation. Businesses may also earn credit for supplemental environmental programs (additional environmental benefits that do not directly address the violation, but are incorporated into an administrative settlement) for developing an EMS.

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2. EPA, State Program Status, available at cfpub.epa.gov/npdes/statestats.cfm.
3. 33 U.S.C. § 1362 (6).
4. 33 U.S.C. § 1362(14).
5. *See e.g. Cordiano v. Metacon Gun Club, Inc.*, 575 F.3d 199 (2d Cir. 2009).
6. 33 C.F.R. § 323.2(c).
7. 33 C.F.R. § 323.2(e).
8. *Id*.
9. *Id*.
10. EPA, Draft Guidance on Identifying Waters Protected by the Clean Water Act, available at www.epa.gov/indian/pdf/wous_guidance_4-2011.pdf; *see also* EPA, Overview of Draft Guidance on Identifying Waters Protected by the Clean Water Act, available at water.epa.gov/lawsregs/guidance/wetlands/CWAwaters_guidesum.cfm.
11. *Id*. A pictorial guide depicting what constitutes a water of the United States under the CWA is also available at www.usace.army.mil/CECW/Documents/cecwo/reg/juris_images.pdf.
12. EPA, National Pollutant Discharge Elimination System (NPDES) - Mining, available at cfpub.epa.gov/npdes/indpermitting/mining.cfm.
13. 40 C.F.R. § 122.2.
14. *See e.g.* EPA, Application for permit to discharge process wastewater for new industrial facilities, available at www.epa.gov/npdes/pubs/3510-2D.pdf.
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16. Office of Wastewater Management - Water Permitting, Water Permitting 101, available at www.epa.gov/npdes/pubs/101pape.pdf
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19. EPA, Stormwater Discharges From Municipal Separate Storm Sewer Systems (MS4), cfpub.epa.gov/npdes/stormwater/munic.cfm.
20. EPA, Stormwater Discharges From Construction Activities, cfpub.epa.gov/npdes/stormwater/const.cfm; *see also* 40 C.F.R. § 122.26(b)(14)(i)-(xi).
21. Specifically, 40 C.F.R. Parts 405-471 include the following categories that may be particularly relevant: (1) discharges from cement manufacturing (as defined in 40 C.F.R. § 411.10); (2) certain coal mines (40 C.F.R. § 434 *et seq.*); (3) mining or quarrying and the processing of crushed and broken stone and riprap (40 C.F.R. § 436 *et seq.*); and (4) ore mining (40 C.F.R. § 440 *et seq*).
22. 40 C.F.R. § 122.26(b)(14)(ii) includes "Facilities classified as Standard Industrial Classifications 24 (except 2434), 26 (except 265 and 267), 28 (except 283), 29, 31l, 32 (except 323), 33, 344l, 373."
23. 40 C.F.R. § 122.26(b)(14)(iii) covers facilities classified as "Standard Industrial Classifications 10 through 14 (mineral industry) including active or inactive mining operations (except for certain areas of coal mining operations) and oil and gas exploration, production, processing or treatment operations or transmission facilities that discharge storm water contaminated by contact with or that has come into contact with, any overburden, raw material, intermediate products, finished products, byproducts or waste products located on the site of such operations."

24. For a chart of the status of each State Program, see: cfpub.epa.gov/npdes/statestats.cfm.
25. EPA, Construction General Permit, cfpub.epa.gov/npdes/stormwater/cgp.cfm.
26. EPA, Categories of Industrial Activity that Require Permit Coverage, cfpub1.epa.gov/npdes/stormwater/swcats.cfm; *see also* 40 C.F.R. § 122.26.
27. *Id*.
28. 76 Fed. Reg. 22882 (Apr. 25, 2011). The CGP is available at cfpub.epa.gov/npdes/stormwater/cgp.cfm.
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30. *Id*.
31. *Id*.
32. *American Mining Congress v. U.S. Army Corps of Engineers*, 951 F.Supp. 267, 269 (D.D.C. 1997).
33. *See e.g. Nat'l Mining Ass'n v. U.S. Army Corps of Engineers*, 145 F.3d 1399, 1401 (D.C. Cir. 1998).
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35. *Id*.
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38. A list of the nationwide permits through 2007 is available at: www.usace.army.mil/CECW/Documents/cecwo/reg/nwp/2007nwp_sum_ table.pdf.
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40. USACE, U.S. Army Corps of Engineers Permitting Process Information, www.lrl.usace.army.mil/orf/article.asp?id=1592&MyCategory=44.
41. *Id*.
42. *Id*.
43. See EPA, National Environmental Policy Act Basic Information, www.epa.gov/compliance/basics/nepa.html.
44. 33 U.S.C. § 1319; 40 C.F.R. § 19.4 (adjusting the amount of civil penalties for inflation).
45. *Id*. at § 1319 (g).
46. *Id*. at § 1319 (d).
47. *Id*. at § 1319 (c).
48. 33 U.S.C. § 1365.
49. Ohio Revised Code, §1501.32.
50. See Kentucky Department of Environmental Protection, Division of Water, water.ky.gov/permitting/Pages/WaterWithdrawalPermitting.aspx A copy of the diversion permit is available at: dep.ky.gov/formslibrary/Documents/StreamDiversionApplication.pdf.
51. Guidelines for Ground-Water Classification Under the EPA Ground-Water Protection Strategy (June 1988).
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Chapter 5
Sustainability

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5.1 Introduction

The National Stone, Sand and Gravel Association (NSSGA) identifies sustainability as a business approach that integrates environmental stewardship, social responsibility and economic prosperity to ensure the long-term supply of aggregates materials to society. NSSGA recognizes that sustainable practices are necessary today to preserve the potential for a quality life for future generations. By pursuing sustainability initiatives through their everyday business practices, NSSGA producer members both large and regional are challenging business norms while maintaining financial success. Many of the efforts now touted as sustainability initiatives are those that are ingrained in the aggregates industry's current business model and are supported and promoted by NSSGA's Sustainability Task Force. Sustainability means that the industry cares about people, about the environment and about making products that help build American's economy.

5.2 What is Sustainability

Dictionaries provide more than 10 meanings for sustainability, the most common one being "the capacity to continue a lifestyle indefinitely."[1, 2] However, since the 1980s sustainability has been used more in the sense of human sustainability on the planet and this has resulted in the most widely quoted definition of sustainability: "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[3, 4] Relating these definitions to business management practices a sustainable business is a non-traditional strategy that strives to maximize effectiveness, restore environmental quality and build social equity while increasing long term profitability.

Sustainability principles are being recognized as the means of meeting business, environmental and social demands of many stakeholders. These initiatives are being driven by businesses that focus beyond current regulatory and policy directives. The businesses that are in the forefront of sustainability are generating a new business model based on technology, information and new forms of value creation.

In 2002, at the World Summit on Sustainability Development in Johannesburg, South Africa, 193 countries, including the United States, concluded that minerals were important to the economic and social development of countries and that social, environmental and economic value were essential considerations for aggregates and mineral operations. In 2007, NSSGA's Board of Directors approved Guiding Principles for Sustainable Aggregates Operations that identify sustainability as a business approach that integrates environmental stewardship, social responsibility and economic prosperity to ensure the long-term supply of aggregates materials to society. The long-term viability of the industry is dependent on obtaining and maintaining a social license to operate. NSSGA member companies will enhance their ability to obtain and maintain these licenses by applying sustainability principles.

5.3 Business Case for Sustainability

Integrating sustainable long-term initiatives into the business decision making process will help drive both business management and product innovation. Utilizing frameworks such as Lifecycle Analysis, Industrial Ecology, Cradle to Grave and Global Reporting Initiatives enable an organization to understand the social and environmental effects of its business and enhance overall performance through a self-directed continuous improvement process.

Through the pursuit of sustainable initiatives, companies are identifying competitive advantages that spur business innovation. The benefits observed by focusing on sustainability include:

- Maintaining an organization's social license to operate within the community;
- Increasing profitability;
- Providing a competitive advantage;
- Identifying and controlling risk;
- Generating additional revenue streams;
- Minimizing environmental impacts; and
- Improving global marketplace penetration.

Some companies focus primarily on production and product development and do not take into consideration other aspects of operations beyond the minimum requirements such as environmental issues or social responsibility within the local community. Lack of foresight and focus on the environmenwtal and social aspects can increase risk and liability which diminish efficiency, control and profitability.

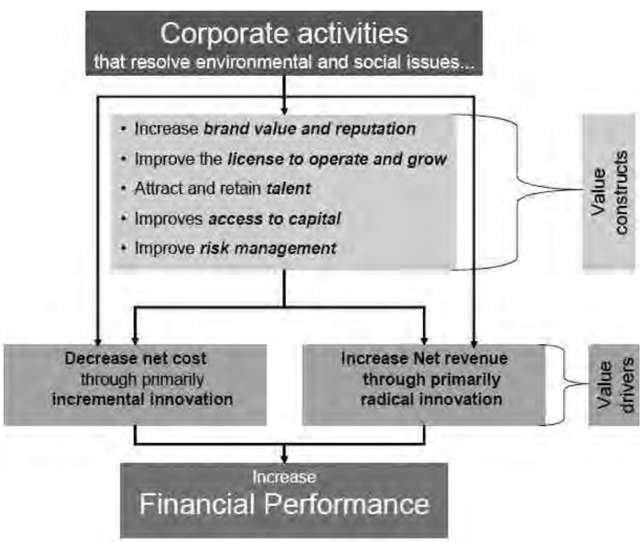

Figure 5.1 Systemization of value drivers and value constructs (Salzmann)

Environmental stewardship and social responsibilities can interact to increase stakeholder value as well as shareholder value. As depicted in Figure 5.1, when corporate activities such as environmental and social issues that pose a risk or liability to an organization are resolved responsibly in a manner that goes beyond meeting legal compliance obligations, competitive advantages, new product and business innovations are identified. These are winning opportunities for the business, the environment and the surrounding community.

The growing interest and momentum in sustainability over the last 20 years is a leading indicator that sustainability is changing the business landscape. As more businesses begin to modify their business model and integrate environmental stewardship and social responsibilities into their decision making process, a more holistic approach to business management, process and product design is beginning to emerge. This is how competitive advantages are identified and where sustainable business innovation occurs, which in turn drive value as depicted in Figure 5.1.

5.4 Triple Bottom Line

The foundation of a sustainable business model, commonly referred to as the Triple Bottom Line, requires the three pillars of sustainability to influence business decisions simultaneously. The three pillars of sustainability include:

- Financial prosperity;
- Environmental stewardship; and
- Social equity.

Many companies operating under the standard business models without a focus on the three pillars of sustainability tend to react to social and environmental risk as they arise, which generally increases the potential liability or cost. Transforming the business model to one that focuses on the Triple Bottom Line will modify this reactive structure to a proactive planning and improvement structure allowing a company to control risks and minimize liability on an ongoing basis. By proactively addressing potential social and environmental risk, an organization will improve its operations with a resultant positive effect on the environment and social position in the local community and ultimately their bottom line.

Developing leadership competencies for superior organizational performance has always been vitally important. Today's business environment is increasingly complex and globally integrated and further is complicated by the additional layers of accountability within the emerging framework of the Triple Bottom Line. The identification and development of critical leadership competencies that address the requirements of the Triple Bottom Line will put an organization on the path to competitive advantage.

5.4.1 Environmental Stewardship

Maintaining environmental compliance can be an expensive but necessary process for businesses. Conforming to environmental laws, quantifying impact, preparing reports and obtaining legal opinions are all expenses to a corporation's bottom line that provide limited return on investment (ROI). An assessment of environmental performance compared to economic performance, as depicted in Figure 5.2 below, suggests that simply maintaining environmental compliance provides the least amount of financial gains over time. Investment in environmental stewardship beyond basic compliance is positively correlated with economic performance.

Figure 5.2 Assessment of Environmental versus Economic Performance, Business and Sustainable Development: A Global Guide, 2010 International Institute for Sustainable Development

Environmental stewardship can be viewed as going beyond maintaining legal environmental compliance obligations. Going beyond compliance means eliminating the applicability of a legal regulation by removing the regulated environmental impact from an operation or significantly out-performing the regulatory standard thereby adding value through improved efficiencies and risk avoidance. An example of pursuing environmental stewardship and going beyond compliance is innovatively modifying an operation to completely eliminate discharges to surface water. Aggregates operations that pursue a sustainable strategy with an emphasis on environmental stewardship tend to focus on the following key areas:

- Environmental management systems
- Air emissions control
- Water management
- The protection of sensitive environmental receptors
- Conservation of natural resources

Each of these key areas is further described below.

5.4.1.1 Environmental Management Systems

An Environmental Management System (EMS) is a set of management tools and principles designed to guide the allocation of resources, assignment of responsibilities and ongoing evaluation of practices, procedures and processes that a company needs to integrate environmental concerns into its daily business practices, thereby promoting environmental stewardship. The EMS developed and outlined by the International Standards Organization (ISO) in its standard ISO 14001 is one such example. The ISO 14001 EMS provides a widely recognized set of principles and standards for integrating environmental management into quality control and other business activities.

- An EMS is a continual cycle of planning, implementing, reviewing and improving the processes and actions that an organization undertakes to meet its environmental obligations.
- EMS models are based on the Plan, Do, Check, Act model which endorses the concept of continual improvement.

(Figure 5.3, see color section)

The benefits of an environmental management system include:

- Improve environmental performance;
- Enhance compliance;
- Prevent pollution and conserve resources;
- Reduce/mitigate risks;
- Increase efficiency/reduce costs;
- Enhance public image with regulators, public, lenders, investors;
- Achieve/improve employee awareness of environmental issues and responsibilities; and
- Qualify the site for recognition/incentive programs such as state level Performance Track environmental recognition programs such as the Arizona Environmental Performance Track (AzEPT), Illinois Governor's Pollution Prevention Awards, Indiana's Governor's Awards for Environmental Excellence and a new national nonprofit program the Stewardship Action Council (SAC) which is continuing to promote the positive performance initiatives and programs of the EPA's Environmental Performance Track.

EPA describes its position on EMSs: "EPA supports and will help promote the development and use of EMSs, including those based on the ISO 14001 standard, that help an organization achieve its environmental obligations and broader environmental performance goals."

In response, NSSGA developed an EMS template for use by its members. The template was created to provide producer members with a written framework that can be used in sections or used in its entirety to develop a voluntary EMS program. While the EMS template follows the general guidelines of ISO 14001, the NSSGA Template takes the form of modules so that each producer member can choose the individual modules and adapt them, as appropriate, to best fit their company's needs and stated environmental goals and principles. NSSGA's EMS model uses a Plan, Do, Check, Act approach, similar to quality management principles, that focuses on continual improvement. This approach ensures that environmental matters are systematically identified, controlled and monitored.

NSSGA's EMS templates guide the user through the development and implementation of an EMS through the following:

- How to use the Template as a guide to implementing an EMS within your organization;
- How to develop an Environmental Policy and a formal analysis to gauge your organization's current environmental programs;
- How to identify the environmental aspects of the activities and services of an organization, determine which are potentially significant environmental impacts; and be able to establish environmental objectives and targets and management plans for achieving them;
- How to implement necessary training, establish appropriate operational controls and measure and monitor the activities associated with the significant environmental aspects;
- How to determine methods for identifying and having access to environmental legal requirements applicable to your operations and be aware of the specific environmental laws and regulations applicable to aggregates operations;
- How to implement the EMS elements of communication, documentation, document control, record keeping and emergency preparedness and response; and
- How to understand the compliance evaluation, EMS audit and management review elements.

5.4.1.2 Air Emissions Control

NSSGA and its members have worked diligently to promote environmental stewardship and improve the nation's air quality. Today, the nation's air is getting cleaner thanks to a number of working partnership that includes aggregates producers. To continue this progress on improving air quality and to avoid the costly economic consequences of increased federal regulations that poor air quality can bring, NSSGA aggregates producers are focusing their efforts to manage and ultimately reduce particulate emissions and green house gas (GHG) emissions throughout the aggregates industry.

The production, processing and use of various minerals can be associated with particulate emissions in the form of dust. Frequently, as in the case of crushing and screening, this dust is identical in composition to the natural crustal material being processed. Emissions also can occur from handling and storing the finished product because this material is often dry and fine. Particulate emissions from some of the processes such as quarrying, yard storage and dust from transport can be difficult to control, but most can be significantly reduced by conventional particulate emissions control equipment such as cyclones, scrubbers and fabric filters.

Additionally, it is very likely that new regulations or new legislation will include mandatory registries that will require monitoring of GHG emissions from a variety of stationary sources, possibly including the aggregates industry. The EPA has a required GHG registry to use as a reporting mechanism for a number of industries. A GHG registry is a database for collecting, verifying and tracking emissions data on a facility or corporate level. Because NSSGA foreshadowed this agency action, the association created a simple spreadsheet calculator that can help members verifiably determine their GHG emission levels for mobile and stationary sources at aggregates, ready mixed concrete, asphalt and pulverized minerals facilities. These concepts and tools developed to effectively manage air quality issues are further described in Chapter 4.

5.4.1.3 Water Management

Water is a critical resource for the communities that the aggregates industry services and also for the aggregates mining and processing operations. Some examples of water management practices used by the aggregates industry that minimize the amount of ground water and surface water consumed by the operation include the following:

- Collection and use/reuse of storm water that falls on the mine site;
- Collection and use/reuse of ground water collected in the quarry pit;
- Collection, treatment and reuse of water from the processing operations;
- Consideration of water usage in the design of equipment such as dust suppression systems; and
- Management of the water levels in the pits and settling ponds to maintain capacity for use and minimize the amount of additional water needed, while ensuring that sufficient storage capacity is maintained to handle storm events and provide effective treatment of the process water.

These water management practices provide social, environmental and economic value in the following ways:

- In many locations, the ability of a mine site to retain large volumes of storm water reduces the risk of flooding and other impacts associate with storm water that otherwise would be discharging into creeks and streams;
- Providing for an adequate supply of water to the mining operation helps ensure that the supply of quality aggregates from the operation is not curtailed and that development in the community that depends on the availability of the aggregates is not interrupted;
- Effective water management reduces the economic cost of water supply to the aggregates operation by reducing the amount of additional water that must be supplied from ground water or surface water sources. The economic savings are associated with usage fees and pumping costs to operate ground water or surface water supply systems; and
- Environmental value is provided through reduction in the volume and sediment loading of discharges from the operations, providing adequate water for dust control within the operation, reduction in impact of storm water runoff to receiving streams by allowing for the controlled discharge when needed following treatment or application of best management practices.

The water management systems at aggregates operation also ensure that water is available for the processing of the aggregates and for dust control during periods of extended drought. Effective management of water resources provides social, environmental and economic value and is an important part of the aggregates industries' sustainability effort. Please refer to Chapter 4 for more information on water management in the aggregates industry.

5.4.1.4 Protection of Sensitive Environmental Receptors

The sustainability of the aggregates industry is dependent on the availability of aggregates resources in areas where the resource can be developed cost effectively and in proximity to the market for the products. The industry does not have the ability to locate in any location, but must locate in an area where the resources are available. In some cases, the locations of the aggregates resources coincides with the presence of sensate environmental receptors, such as lakes, streams, wetlands, threatened and endangered species, historic or cultural resources and other types of sensitive receptors. The ability of the industry to minimize impacts to these sensitive receptors and comply with all regulatory requirements associated with evaluation and mitigation of impacts, are important aspects to the industry's sustainability efforts. In addition to the information in the following sections , please refer to Chapter 4 for more information on sensitive environmental receptors associated with the aggregates industry.

5.4.1.4.1 Wetlands

Aggregates mining operations often are located in proximity to streams and other water features, including areas that qualify as jurisdictional wetlands either under the Federal Clean Water Act or state-specific laws and regulations. The definitional issue relative to water features considered to be subject to federal jurisdiction, including wetland areas, has been under constant challenge for many years and is still subject to change. This increases the importance for aggregates operators to understand whether there are any areas associated with the operation that could be considered jurisdictional wetlands.

The aggregates industry addresses wetland issues in the following ways:

- Identification of areas associated with current or future mining operations that could be classified as jurisdictional wetlands, either federally or at a state level;
- Suspected wetlands areas are evaluated to determine if they are jurisdictional and also to determine the potential impact of the operation on the wetland area;
- In advance of disturbance of the potential jurisdictional wetland, the aggregates operator pursues a determination of jurisdiction that defines the area of impact that is of concern and helps the operator evaluate regulatory and permitting options;
- If disturbance of the wetland area cannot be avoided through change in the mine plan, the aggregates operator will pursue the necessary agency approvals and permits to conduct the planned activity; and
- In conjunction with the necessary agency approvals, aggregates operators often reclaim, enhance, or construct new wetland areas to mitigate the impact of their operations.

In cases where areas are jurisdictional wetlands and impacts cannot be avoided, the aggregates operators pursue the required permits and authorizations, and perform mitigation as required by the agencies. In many cases, aggregates operators mitigate by using portions of their property to either establish or expand the amount of wetlands present at the operation. In other cases, mitigation may involve purchasing credits from wetland mitigation banks. The net effect is that aggregates mining operations avoid disturbance of wetland areas to the extent possible and in cases where the areas will be impacted the necessary authorization, permits and mitigating measures are taken to address any impacts. In many cases, mitigation measures require establishment or preservation of more wetland acreage than what is being disturbed. The industry's approach to wetlands management provides for the preservation and protection of wetlands while allowing the development of aggregates resources. This provides sustainable value by ensuring a long-term viable supply of construction aggregates to the local community and providing for the net protection and preservation of wetlands acreage.

5.4.1.4.2 Threatened and Endangered Species

The large amounts of acreage owned and controlled by the aggregates industry provides habitat for plant and animal species that in some cases are listed as federal and/or state threatened or endangered species. Undisturbed portions of aggregates operations can provide a safe haven for these listed species and thus provide cultural and environmental value through species preservation. In some cases, aggregates operations provide sufficient habitat for listed species where areas of the property are set aside for use as mitigation banks. These mitigation banks provide economic and cultural value by serving as a means of mitigation thus allowing other development projects to proceed supporting the growth of the communities the aggregates operations service.

The presence of listed species or their habitat on property to be developed for aggregates mining and production operations can affect the operations if the proper agency reviews, authorizations and permits are not obtained. Through careful planning and evaluation of the potential for the presence of listed species, the operator has the ability to incorporate actions to protect or address impacts to listed species into the site development and operation. By doing so, aggregates operations provide environmental value through species preservation, economic value by reducing the impact of the species on the operation and that the aggregates resources are available for extraction and processing into products.

5.4.1.4.3 Cultural and Historic Resources

The presence of cultural and historic resources on lands owned and controlled by aggregates operations is not uncommon, primarily due to the large acreages associated with these operations and the frequent connection between the aggregates resources such as historic stream channels and the locations of historic cultures that followed the rivers and streams as sources of water, food and transportation. Much like wetlands and threatened and endangered species, the aggregates industry plays an important role in helping to protect and preserve cultural and historic resources that are present on property associated with their operations. The presence of these resources may be identified during the planning stages for an operation, or may be discovered in the course of land clearing and excavation associated with the mining operation. In either case, once a resource is identified, the necessary government agencies are engaged to determine if preservation is warranted and to ensure the necessary actions are taken to do so.

There are many examples in the aggregates industry where companies have both preserved and restored historic and cultural resources such as old structures, historic graveyards, locations and artifacts from Native American villages, etc. Through these sustainability efforts the industry provides cultural, economic and environmental value to the communities which the industry serves.

5.4.1.5 Conservation of Natural Resources

Conservation of natural resources refers to the management of natural resources such as land, water, soil, plants and animals, with a particular focus on how management affects the quality of life for both present and future generations (stewardship). Natural resource management is congruent with the concept of sustainable development, a scientific principle that forms a basis for sustainable global land management and environmental governance to conserve and preserve natural resources.

NSSGA encourages its members to develop positive relationships with environmental non-profit organizations (NGOs), to promote natural resource conservation. Areas where the aggregates industry can influence and promote conservation efforts include:

- Water
- Energy
- Waste Minimization
- Life-cycle re-use
- Land-use development, planning and management

Each of these key areas is further described below.

5.4.1.5.1 Water Conservation

Water conservation is very important to the aggregates industry like it is to the communities which we serve. The industry depends on the availability of water at an economically viable cost in order to produce the high quality aggregates products our customers require and to provide a necessary resource to control dust emissions from the aggregates operation. The ability of the industry to use water in a manner that conserves the resource is tied to the sustainability of the industry.

The industry water management systems provide water needed for the operation, but in a manner that minimizes the consumption of water that must be withdrawn from ground water and surface water resources. Some of the steps that the industry takes to conserve water include the following:

- Utilization of storm water that falls on the mine property and ground water from intrusion into the quarry pit, which is recovered to supply water for the processing operations and for dust control. By using these sources of water that otherwise would need to be pumped and discharged or be lost though evaporation and storm water runoff, the industry minimizes the amount of water that must be supplied from other sources.

- Collection and treatment of water generated from the processing operations so that the water can be reused, thus reducing the amount of make-up water needed and minimizing the amount of process waste water that would need to be discharged.
- Implementing water conservation measures within the process that reduce the amount of water needed to produce a quality product, such as more efficient aggregates washing processes and the use of high pressure low volume dust suppression systems.

5.4.1.5.2 Energy Conservation

The activities involved in producing aggregates products can be energy intensive; therefore, energy conservation is an important part of the industry's sustainability effort. The major uses of energy involved in production operations include:

- Fuel consumption associated with the operation of mobile equipment used to excavate, load, haul and stockpile the aggregates throughout the production process.
- Electricity consumption associated with the crushing, screening and conveying operations that are necessary to process the mined rock into finished product. Additional electricity consumption is associated with the operation of pumps to supply water to the process and to dewater pits and other miscellaneous equipment which operates off of electricity as the power source.
- The distribution and delivery of the aggregates to the customer requires significant fuel needed to power the trucks, trains, barges and ships.

The cost associated with energy use is a significant portion of the operating cost for the industry. This connection between energy consumption and operating cost drives the industry to constantly evaluate opportunities to reduce energy consumption. Energy conservation measures are directly related to the economic sustainability of the industry and also provide social value by reducing the amount of fuel that is used across the country, ultimately decreasing the dependence on imported oil and increasing the lifetime of the oil reserves available in this country. Energy conservation has environmental benefits by reducing the amount of air pollutants emitted associated with the direct combustion of the fuel in the equipment, as well as the indirect emissions associated with the production of electricity.

5.4.1.5.3 Waste Minimization Through Source Reduction and Recycling

The aggregates industry generates various materials that once discarded are considered waste. The amount of waste generated by the aggregates industry is reduced through the application of waste minimization, with aggregates operators focusing on ways to reduce the generation of waste through source reductions and also through material reuse and recycling. Some examples of waste minimization practices used by the industry include:

- Implementation of equipment maintenance practices that extend the useful life of equipment and reduce the frequency of maintenance. Examples of these practices include the use of extended life anti-freezes and motor oils, periodic testing of lubricants and coolants as a means of determining when service is needed and monitoring of tire pressure to extend tire life.

- Use of non-hazardous alternatives such as citrus based cleaning products to minimize hazardous materials use.
- Reduction in the amount of petroleum contaminated material that must be disposed through installation of containments and pads in locations where petroleum product transfer and fueling operations occur and use of spill containment and response equipment to minimize the risk of generating contaminated soil if a spill were to occur.
- Recycling of light bulbs, batteries and electronic equipment.
- Identifying alternative uses for materials such as conveyor belts, tires, screen decks, etc.
- Use of a scrap recycler for management of steel and other scrap metals.
- On-site use of overburden for construction of site berms and other features to the extent practical.

These examples are not comprehensive but do illustrate that the industry applies a broad range of waste minimization practices to the extent feasible on a facility specific basis. The waste minimization practices provide sustainable value through reductions in the following:

- Operating costs associated with material procurement and waste disposal fees (economic value).
- The amount of material that must be disposed of as a waste thus reducing the burden placed on local and regional landfills and other waste management facilities; and by allowing for the recovery for re-use of materials such as mercury contained in light bulbs and other electronic equipment (environmental value).

5.4.1.5.4 Life-Cycle Re-use (Aggregates as 100 percent Recyclable Material)

The aggregates industry produces a material that is naturally occurring and that has limited although currently abundant reserves available. The limitation is not based strictly on the amount of aggregates present in the earth, but on the quantity of reserves that are recoverable and permitted for extraction. This limitation is a concern to individual operations that have a finite amount of reserves that are permitted for recovery and processing. Construction applications such as the production of concrete, hot-mix asphalt and foundation; and roadway construction, repair, etc., comprise a large portion of the end-uses for aggregates products. While the durability of the aggregates helps promote a long lifetime of the aggregates product within these structures and applications, eventually the useful life will end and the structures will be demolished. The aggregates that are incorporated into these structures once demolished can be readily recovered for re-use by crushing the concrete or asphalt and separating the aggregates material. Once recovered, the aggregates can be re-used in much the same way as the original aggregates was specified. Re-using the aggregates in this manner provides the following sustainability values:

- The economics of recycling aggregates material vary based on the operation and the cost associated with the supply of the recycled aggregates material but generally the recycled material should be available for a comparable cost to the production cost of the aggregates from the mining operation;

- Recycling aggregates material reduces the need for disposal of the material thereby generating environmental benefits; and
- Extending the life of existing operations reduces the need to locate and permit new aggregates mining and processing operations which improves social capital.

The ability to re-use aggregates materials extends the life-cycle of the aggregates and also of the mining operation. This provides benefits to the aggregates producer as well as to the communities that the producer serves.

5.4.1.5.5 Land-use Development, Planning and Management (refer to Chapter 4)

Aggregates production operations can be considered an interim land use given that the aggregates operation has a limited lifetime. Understanding the anticipated post-mining land use is valuable for several reasons including:

- Allows for engagement of key stakeholders such as the community in the mine planning process. This has value as a means of securing buy-in from external stakeholders in the mining process and assisting in the permitting and land use authorization process.
- Enables the mine site to be developed in a manner consistent with the end use of the property which can increase the efficiency of reclamation activities.
- Mine sites developed with an end use in mind allow the operator to identify opportunities for use of the property that provide economic value beyond the cessation in mining. For example, developing the site for commercial development in many areas can provide significant economic value to the operator and the community.
- Re-development provides an extended use for property that would otherwise represent a liability for the aggregates producer as a vacant, unreclaimed site.

Consideration of the post-mining use of aggregates production sites is an important component of a producer's sustainability program. Mine reclamation provides social value by leaving a resource for the community versus a piece of abandoned property, economic value by providing future land use opportunities and environmental value by ensuring the property is developed in a manner protective of the natural environment. The value of the land owned and controlled by aggregates producers goes beyond its current use as a source of construction aggregates and provides long-term sustainable benefit to the community.

5.4.1.6 Social Progress

Social progress is the idea that businesses can improve their social, political and economic business model structures. This may happen as a result of direct human action, as in social enterprises, or through social activities.

As an engine for social progress, sustainable social initiatives encourage companies to act as a responsible global citizen and local neighbor in a fast-changing world. Acting in a socially responsible manner is more than just an ethical duty for a company but is something that actually has a bottom line pay-off. Aggregates producers can be large scale multi-national companies or regional local producers. Whether large or small, each aggregates producer is encouraged to seek stronger relationships and develop initiatives with not only their employees but also the communities that they operate within as described below.

5.4.1.6.1 Community

While they may belong to a national organization, aggregates producers are, most importantly, members of local communities. As such, they make important contributions – and have equally important responsibilities – to their neighbors. NSSGA members are encouraged to engage community leaders and residents in open, honest and effective collaborations about plant operations.

Throughout the industry there is a new awareness of the necessity for producers to respect the cultures and values of neighbors who may be affected by aggregates operation and the necessity to reduce to acceptable levels any adverse impact caused by those operations. Producers have always made a positive contribution to their communities by hiring local workers and purchasing local goods. Today, producers are contributing in many other ways such as providing educational outreach about aggregates use and looking for opportunities to provide local infrastructure improvements.

In the U.S., the most successful aggregates companies enjoy the consent of the public to do business. This is called obtaining a "social license to operate." Companies lacking public consent rarely survive. While a company has the ability to control its image, the public controls its ability to operate. Having a poor image in the community will lead only to confrontation and denial of a social and regulatory license to operate.

NSSGA encourages its member companies to establish long-term community relations programs that involve community leaders at all levels, particularly among elected and appointed government leaders, educators and opinion makers. NSSGA provides publications and materials that guide members through the planning and execution of community relations programs and educational materials that can be used for public engagement in schools or civic settings. NSSGA recognizes member efforts annually through its Excellence in Community Relations Awards program.

5.4.1.6.2 Employees

For every $1 million of output produced by the industry, 19.5 jobs are created. The direct output of the aggregates industry supported a total of more than 281,000 full-time equivalent jobs including both direct jobs (jobs in the industry) and jobs supported by the industry's spending (payroll spending and spending by suppliers). These jobs supported total personal earnings in excess of $11 billion.

The industry also is proactive and goes beyond compliance with the relationship between the company and employees. Health and safety regulations are stringent in the mining industry but a sustainable company will ensure that its workers have access to the latest equipment in order to operate safely. This includes the use of personal protective equipment which helps to guard against injury and the institution of a long-term occupational health program which helps to ensure a healthy workplace for years to come. All of the good community work will be worthless without excellent safety and health performance.

A diverse and well-trained workforce allows different voices to be heard and helps to create an environment that fosters change and innovation. Sustainable companies recognize that the workforce is changing and endeavor to provide necessary training and have their staff match the demographics of the neighboring community.

A well-trained workforce helps operations run more efficiently, helps employees to operate equipment safely and effectively, and creates opportunities for them to be familiar with aspects of the facility beyond just their job.

5.4.1.7

5.4.1.7.1 Contribution of the Aggregates Industry to U.S. Economic Prosperity and Communities in Which We Operate

Aggregates are basic and fundamental to the building blocks of society and a strong economy. They are the essential ingredients of the nation's infrastructure – its transportation systems, sewer and water systems and public facilities – that are required to support a growing and healthy economy. The aggregates industry also is a significant source of employment and income nationally and especially in the communities with aggregates operations. This industry produces major and essential contributions to many other industries across the breadth of the national economy. It makes significant contributions to the GDP and the economies of many states. Contributing to the nation's agriculture, manufacturing and construction industries, the aggregates industry provides the foundation for the nation's economic vitality. The importance of this industry can be measured by the value of its outputs and their contribution to the intermediate and final products of industries that use aggregates in the production process.

It is even more significant than its numbers suggest because of its fundamental contribution to the physical capacity of the national and state economies, their production of goods and services and to the support of a high quality and productive environment for U.S. businesses and residents.

- Aggregates production accounts for more than half of the non-fuel mining volume in the U.S.
- 38,000 tons of aggregates are necessary to construct one mile of a four-lane highway.
- 400 tons are required to build an average modern home.
- 5,000 tons are required to build a 100,000 square foot office building.

- For every dollar of output in the industry, an additional $1.58 is generated in the national economy.

Every American Born Will Need ...

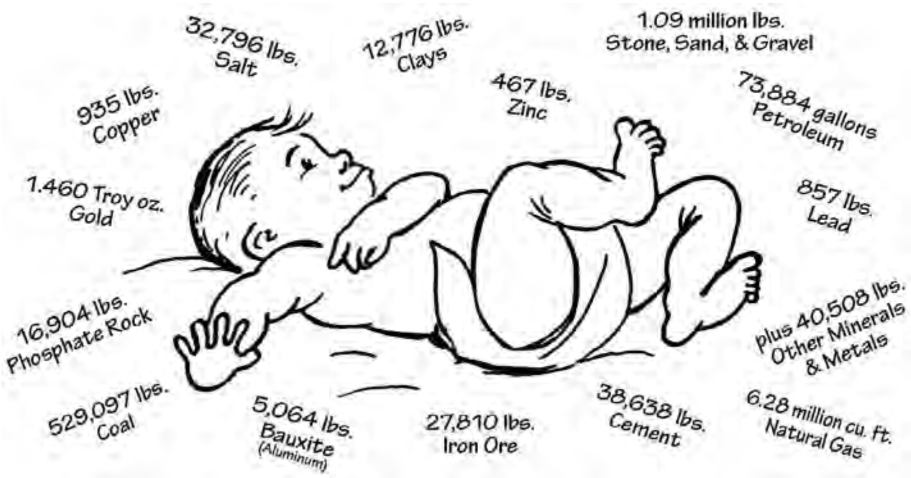

Figure 5.4 courtesy of the Mineral Information Institute.

3.3 million pounds of minerals, metals and fuel in their lifetime.

The long-term viability of the industry is dependent on obtaining and maintaining a social license to operate. As a society, Americans must develop an appropriate balance for sustaining both aggregates resources and environmental resources. Sustainable aggregates resource management recognizes the importance of the industry as a key sector of the economy that contributes jobs and a high-quality of life and wealth for its citizens. Social licenses to operate are based on discretionary decisions by local government bodies that are heavily influenced by political and public opinion. Aggregates companies enhance their ability to obtain these licenses when applying sustainability initiatives.

5.4.1.7.2 Developing Standards

Long-term sustainability is achieved when practical research is applied to improve the quality of life in the communities in which we operate.

NSSGA through its research foundation, the Aggregates Foundation for Technology, Research and Education (AFTRE), has supported research projects that investigate new ways to extend aggregates resources and support technology transfer that moves such research into the marketplace. AFTRE funded a wide range of aggregates industry research for new and more efficient ways to use finite resources. Examples include identification of aggregates base course layers that can be placed in 12- to 18-inch lifts instead of 6- to 8-inch lifts. The corresponding savings in labor, time and overall cost of placement saves energy and increases the efficiency of road construction. Other research focuses on topics such as concrete and hot mix asphalt mix designs, use of microfines (materials finer than 0.75 um) in mixtures, new test methods, aggregates base course design and more. Overall, research reconsiders current methods and usage and leads to innovation that ultimately improves how aggregates and other resources are used.

The development of aggregates specifications and standards is crucial as to whether or not aggregates will be available in amounts adequate to support and sustain the growth of the U.S. economy. For this reason, NSSGA and its member companies actively participate in the American Society for Testing and Materials (ASTM), one of the largest voluntary standards development organizations in the world and work closely with state and local aggregates user agencies to establish standard specifications and test methods that support full use of aggregates resources.

ASTM is a well-respected and internationally recognized source for technical standards for materials, products, systems and services. Known for their high technical quality and market relevancy, ASTM International standards have an important role in the information infrastructure that guides design, manufacturing and trade in the global economy.

In both the lab and the field, NSSGA works to develop solutions to the regulatory challenges that confront the industry. NSSGA's air emissions research, conducted in cooperation with EPA, has lead to the aggregates industry not being considered a major source of particulate matter emissions by state and federal regulatory agencies, thus saving the industry hundreds of thousands of dollars in permit fees and unneeded control devices. Industry air quality research has also bolstered EPA's conclusions that maintenance of existing ambient air quality standards are adequate to protect the general public's health and welfare from ambient exposure to crystalline silica.

5.5 Business Ethics

It is universally acknowledged that eliminating corruption is a prerequisite for societal and economic development. Good governance and transparency are building blocks of modern democratic societies. The question no longer is whether corruption hinders sustainable development, but much more how societal actors can collaborate to eliminate corruption in all its forms, including bribery and extortion. The subject of business ethics addresses what can be considered morally right and wrong in the way businesses make decisions and conduct their activities. Significant corruption risks in business include procurement fraud and companies who engage in corrupt practices involving governments. The direct costs of the corruption are considerable, including product quality, but are often dwarfed by indirect costs related to management time and resources spent dealing with issues such as legal liability and damage to a company's reputation. Companies that engage with their supply chains, local governments and communities through meaningful anti-corruption programs can improve product quality, reduce fraud and related costs, enhance their reputations for honest business conduct, improve the environment for business and create a more sustainable platform for future growth.

Sustainability encourages companies to embrace, support and enact, within their sphere of influence, a set of core values in the areas of human rights, labor standards and the environment. The principles are as follows:

Human Rights

- Businesses should support and respect the protection of internationally proclaimed human rights; and
- Make sure that they are not complicit in human rights abuses.

Labor

- The elimination of all forms of forced and compulsory labor;
- The effective abolition of child labor; and
- The elimination of discrimination in respect to employment and occupation.

Environment

- Businesses should support a precautionary approach to environmental challenges (i.e., Principle 15 of the 1992 Rio Declaration states that "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation");
- Undertake initiatives to promote greater environmental responsibility; and
- Encourage the development and diffusion of environmentally friendly technologies.

Anti-Corruption

- Businesses should work against corruption in all its forms, including extortion and bribery.

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Chapter 6
Industry Health and Safety

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6.1 Introduction

From its beginnings, quarrying and mining for aggregates has been characterized as a dangerous industry. This unenviable reputation was born from the historically unacceptable work conditions and loss statistics that described the industry in its earlier days.

Over the decades, work conditions, equipment, tools and processes have improved significantly, such that mining is now among the safest industries in the U.S. (National Safety Council). Much of that change resulted from a more modern perspective in society and industry regarding the value of life and acceptable personal and business risk.

Earning a living should not require exposure to chemical or physical agents, products or processes that create an excess health and/or safety risk. This sentiment is enforced by the U.S. Mine Safety and Health Administration (MSHA), the U. S. Occupational Safety and Health Administration (OSHA) and other regulatory agencies. However, compliance alone is no guarantee of high-level safety performance. There are many more factors that are not amenable to regulation—such as human behavior, work culture and leadership—that play a significant role in worker protection.

For the modern manager and business leader, advancing safety and health performance within the business is essential to maintaining the wellbeing of their employees as well as a successful career. Achieving the highest level of safety and health performance requires an understanding of safety and health management systems, work culture, behavior modification and regulations, for example, and knowing how to make those elements all work together in an already dynamic environment.

Accordingly, this chapter is intended to provide direction to those leaders who recognize that maximizing safety and health performance is a business necessity—in addition to being the right thing to do.

The aggregates work environment presents a mix of potential safety and health concerns. These concerns include the use of mobile equipment, stationary equipment with moving parts (e.g., conveyors), working from heights or within confined spaces, explosives use and working with electrical components, to name a few. Common health hazards include mineral dust (particularly respirable crystalline silica), noise, ergonomics, chemical exposures, welding fumes, thermal stress, solar radiation and vibration.

Personal lifestyle factors also contribute to workplace safety and health, affect absenteeism rates and impact personal health insurance claims (and insurance premiums) by employees and their families. Consequently, many employers today incentivize employees and their families to reduce overall risk through positive lifestyle choices, for example, sensible nutrition ("eating right") and exercise, defensive driving, avoiding tobacco, drugs and alcohol and so forth.

To minimize or eliminate workplace hazards, the successful manager will thoroughly understand and implement a safety and health management program to keep his or her employees safe and to achieve and sustain excellence in the aggregates industry.

6.2 Historical Background, Industry Awareness

Worker safety and the associated safe-work practices have long been an important concern of the management of companies that produce aggregates.[i] In 1926 the aggregates industry and the U.S. Bureau of Mines began an annual safety recognition program. The joint program focused the attention of management and labor on the fundamental importance of a safe workplace and safe work habits, and proved the business value of both. Although the Bureau of Mines no longer exists, NSSGA's annual safety program and the Sentinels of Safety awards program continue to this day.

Proof that these programs work is the fact that, in 2010, aggregates mining fatalities totaled nine, industry wide, compared with more than 3,000 annual mining fatalities when statistics first were tracked in 1910. Nine fatalities are still unacceptable by any reckoning, but the trend is overwhelmingly clear. Moreover, in 2011, the total incident rates per 200,000 hours worked in the aggregates industry was just 2.27, a value that compares favorably with, for example, the 1993 rate of 6.1.

6.3 Safety Programs

MSHA, through its regulation and inspection activity, enforces minimum levels of protection of mine workers' safety and health. The term "minimum" is used intentionally to emphasize the operators' responsibility to provide a safe and healthful work place for all employees. Ultimately, however, an aggregates facility's safety and health program is only as effective as the hazard awareness, safety and health consciousness, and worker attitude that the operator instills in all employees associated with the mine. It should be stressed that facility operators are responsible for the safety and health of all individuals working at the mine site, including those persons who may be non-company employees engaged in contract work at the mine. The aggregates operator is obligated by law and regulation to provide such contractor employees with adequate hazard training so that they, too, are aware of the hazards as well as the safe work practices unique to individual mine sites.

A successful safety and health program consists of more than simply complying with federal and state rules and regulations. Employers and workers must become aware not only of regulatory requirements, but also what truly constitutes safe and healthful work practices.

World-class safety and health programs have three interdependent features that are critical for success: systems, culture and leadership. Without any one of these three components, success is difficult, at best. Leadership and systems are semi-tangible features, but how do we define culture?

Culture is the sum of the shared beliefs within an organization. Organizations with a strong safety culture share some basic elements that contribute to their performance. These include:

- Management personnel, from the chief executive on down, must have a credible commitment to a safe and healthful work place, and they must actively demonstrate this commitment on a continuous basis.
- There must be open communication among all levels in the organization.
- Trust and confidence must be established both upward and downward in the organization.
- The safety and health policies of the organization must live—or be visibly obvious in the work-place.
- Positive recognition for safety successes and innovations must be established.
- Resources should be spent in appropriate proportions on activities to maintain welfare of employees and production improvements.
- Employees at all levels should have opportunities for decision making and problem solving on safety issues.
- Appropriate metrics must be established that drive supervisory performance and accountability measures in place to ensure they are meaningful.

In short, a "think safety" attitude must be nurtured in each operating unit within the aggregates industry. A safe and healthful work place must become the responsibility and goal of each employer and consequently every employee.

A working safety and health program is good for not only the individual worker but also for the aggregates operator. A safe and healthful work environment is just good business and has a direct impact on an aggregates company's profits through reduced insurance claims and premiums. Higher worker morale attributable to a clean, safe work environment can also result in higher productivity and lower production costs.

Accidents, whether fatal or not, and work-related illnesses, whether debilitating or not, are expensive in terms of pain, suffering, loss of morale, loss of time and disruption of work. Good business practice has helped encourage the aggregates industry to develop strong health and safety awareness programs that go beyond the minimum standards of performance defined by the MSHA regulations and enforcement activities under the federal Mine Safety and Health Act. If any area of company activity deserves an emphasis regarding a *commitment to excellence*, it is the employee health and safety program. The benefits and rewards of such a continuing commitment to health and safety far outweigh the costs of minimum compliance or neglect.

Operator Safety and Health Program Corporate Commitment

Management commitment is imperative to the success of a safety and health program. That is because management both controls the resources necessary to make the program operate, and also influences the corporate culture through its attitude about worker safety and health. Management must provide an unambiguous mission statement and list the goals of an effective safety and health program. It must make the mission and goals known to all employees and must continuously re-emphasize the importance of accomplishing them. It must provide the necessary resources, support employee- and staff-generated safety and health initiatives, and by its own actions set an example for the entire workforce to follow.

Roles and Responsibilities

In a successfully managed safety program, every individual—employees, supervisors, senior management and safety and health professionals—have responsibilities for success. It is important to structure an accountability process that starts by clearly stating each individual's responsibilities and objectives to safely meeting the operation's production needs. Once objectives have been established and agreed upon, periodic performance evaluations must then be completed to provide feedback to employees on whether or not they are meeting expectations.

The purpose of performance evaluations is to establish accountability, and, without accountability, the program cannot be optimally effective. To accomplish this requires judging the work of managers, supervisors, employees and safety and health professionals in formal performance evaluations, the results of which have a direct effect on measures important to employees, such as salary raises, promotions, and specified benefits. Excellence should be rewarded, and such rewards should be widely publicized as an incentive to others.

Safety and Health Committees

Safety and health committees can be a tremendous asset to a good safety program. Each worksite should establish at least one such committee. It should be made up of employees, who volunteer to participate, with management representation. Such committees can identify and report hazards, conduct workplace evaluations, investigate accidents, assist with training, follow-up to determine if remedial efforts are in place and effective, and generally promote safe and healthful behavior both on and off the job. Carefully defining the committee's responsibilities will help to ensure that members remain focused on improving safety.

To support success, safety committee members should receive appropriate training. Knowing how to work and act safely and healthfully cannot be assumed. Management at a minimum has both a legal and moral responsibility to inform employees of the hazards and potential hazards they face on the job.

Training must be an ongoing process, taking into account the hazard potential of changes such as new processes, procedures and equipment. Training also should be based on the latest adult learning techniques and utilize modern educational delivery systems. Besides educating employees on workplace hazards and how to avoid and/or control them, an effective training program is important in instilling a positive safety culture among the workforce.

Recordkeeping is an essential component of a quality safety and health program. Records are useful for numerous purposes including evaluating overall program performance, regulatory oversight and epidemiological studies. Many records, particularly monitoring data, should be entered into a computerized relational database, in which relationships among data can easily be demonstrated.

Hazard Identification, Evaluation and Control

This activity assumes the process will be applied to the existing work environment; however, it is equally important to apply it to equipment and purchased goods (such as chemicals) that enter or leave the work environment as well.

Identifying, thoroughly evaluating and controlling hazards must be a continuous process. Widely recognized methods to identify potential problems include:

- Walk-through surveys
- Special assessments
- Announced and unannounced inspections
- Job safety analyses
- Fact sheets on hazardous materials such as Material Safety Data Sheets

These tasks generally are delegated to safety and health professionals, but employees can play an important role as well and should be actively involved in the process.

All accidents should be vigorously and promptly investigated with the express purpose of determining the root causes, and designing then implementing remedial measures so that the accident has a low probability of recurring. All such investigations should be thoroughly documented with reports. Operators are encouraged to share investigation results throughout the organization. Investigations of accidents should never be conducted to assign blame.

There is a well-established hierarchy of control used when evaluating hazard controls. It starts with the most effective and progresses to the least effective. Personal protective equipment, which is often the first choice, may be the least effective means of hazard control. The hierarchy of control is:

- Engineer or design to eliminate or minimize the hazard;
- Establish guarding to isolate the hazard;
- Provide warning signs and/or alarms to warn against the hazard;
- Provide special procedures and training to avoid the hazard; and
- Provide personal protective equipment to protect the employee.

MacCollum[70] cautions that a means of control that is lower in the order of precedence must never be used when a higher one is feasible. Moreover, the use of several preventive measures, rather than one measure alone, is often necessary, particularly for high-risk hazards.

Program Audits; Continuous Improvement

Appropriately trained and experienced individuals should periodically evaluate the entire program using leading and lagging indicators of program effectiveness.

Leading indicators precede adverse events in time and should have a demonstrated (or at least reasonably anticipated) correlation with adverse events or hazardous conditions. Some leading indicators include, for example:

- The presence and quality of a particular written program;
- The percentage of employees who have successfully received safety training;
- The percentage of air and noise sample results that are less than some fraction of the OEL; and
- The number of actionable safety suggestions or percentage of employees who actively participate in safety committees.

Lagging indicators, which follow an adverse event, include largely measurable criteria such as workers compensation data and accident and illness incidence rates.

Both direct and indirect program costs versus benefits should be compared and the impact of this assessment applied in business terms to the company's bottom line. Adjustments should be made where necessary to ensure continuous improvement.

A widely used formula for determining injury and illness rates is:

$$\text{Incidence Rate} = \frac{\text{\# Reportable injures x 200,000 work hours}}{\text{\# of work hours actually worked during the period}}$$

This is the theoretical percentage of employees who may suffer a recordable injury; 200,000 work-hours is equivalent to the time worked by 100 employees during a typical year (50 weeks at 40 hours per week). For example, a site with three recordable injuries that worked 175,000 work hours during the year would have an incident rate of [(3 x 200,000)/175,000] = 3.4.

The safety and health program is but one of numerous functions (operations, sales and marketing, human resources, accounting, and legal) a company must employ to assure the financial health and long-term viability of its business undertaking, and as such requires measurement of overall program performance. An effective safety and health program should have a continuing, positive impact on the bottom line, thereby underscoring its value to management as well as preventing injuries among the company's employees.

Contractor Safety and Health Program

Mine operators increasingly use contractors to perform specialized tasks, such as drilling, blasting, demolition and maintenance. With more and more contractors working on mine properties, accidents involving contractors are increasing. While the safety and health of contractor employees is the contractor's direct responsibility, there are several reasons that an operator must be concerned about the contractor's safety and health program.

First, there is a practical obligation to establish clear guidelines for managing the safety of contractors and their interaction with your employees. Additionally, under certain circumstances, MSHA may cite the mine operator for a contractor's violations.

Further, a mine operator may be subject to third-party liability if a contractor employee is injured. Injuries to contractors reflect negatively on the industry as a whole because, when accidents are reported on mine sites, the public considers them mine accidents, per se.

Following is an outline of a Contractor Safety and Health program:

1. Statement of Purpose

2. Contractor Provides
   - Pre-contract approval process
   - MSHA and OSHA citation history
   - Injury/illness incidence rates
   - Written safety program and MSDSs
   - Procedures related to specific job tasks
   - Staffing and responsibilities
   - Training programs and MSHA-required training records
   - A certificate of insurance with appropriate risk levels for insurance coverage and showing the mine operator as an additional named insured

3. Pre-Job Meeting
   - Inspect and review site-specific hazards
   - Key personnel introductions

4. Contract Provisions
   - Addresses rights and recourse of operator if contractor does not comply, including contract termination and indemnification.

5. Site-Specific Safety and Health Rules
   Take from existing program or summarize MSHA rules on (for example):
   - Fall protection
   - Confined spaces
   - Personal protective equipment

- Lock-out/Tag-out
- Housekeeping
- Traffic rules
- Vehicle use
- Fire safety
- Hot work
- Accident reporting
- Emergency evacuation

6. Evolution of Contractor Performance

6.4 Selected General Safety Guidelines for Aggregates Operations

Implementing a strong safety program is essential to any aggregates operation. MSHA has specific safety training requirements for mining operations that are mandated under the 1977 Mine Safety and Health Act, as well as 30 CFR Parts 46 and 48. Operators must obtain MSHA approval of training programs, and all miners must receive training before they first begin work, undertake new tasks or assignments, or are transferred to a new work location.

In addition to MSHA's training requirements, there are a number of basic safety principles that should be followed at all operations. The National Safety Council recommends the following general safety guidelines:

- Report all accidents, near-accidents or unsafe conditions to the supervisor immediately, whether or not there is personal injury or damage to equipment. To handle emergency situations, the company should have a rescue team specially trained in emergency medical, firefighting and rescue procedures.

- Wear approved safety glasses, hard hats and hard-toed safety shoes, and other required personal protective equipment at all times, except in designated areas. Safety shoes should be over-the-ankle style and should be a minimum of six inches high.

- Maintain good housekeeping practices in the work area as a normal part of job duties. Dispose of scraps, rags and other combustible materials in covered metal containers. Keep aisles, passageways and stairways free of obstructions, and clear access ways to exits, switchboard, and emergency equipment. Be sure that tools and other equipment do not create a tripping hazard.

- Turn off and lock *(lock out)* all machinery controls and power sources before starting any repair or test work. Anything that cannot be locked out must be tagged out. If two or more people are working on a piece of equipment at the same time, each employee must have a lock or tag on the lockout device. Equipment that has been locked out must be tested before work is begun to verify that lockout has established a zero energy condition.

- Be sure all guards and safety devices are maintained in good condition. Never remove or disable guards or safety devices, except for repair or test work. Before using assigned machinery or equipment, make all necessary safety pre-operational checks. Never get on or off a moving vehicle or piece of equipment.

- If machinery or heavy equipment comes in contact with an electrical source, such as a power line or power cable, stay in the cab, out of contact with the ground, until receiving notification that the power is off.

- When moving power cables, use the proper tools. Do not handle energized power cables unless properly trained to do so, while wearing the proper rubber gloves, and while using properly insulated cable tongs.

- Only designated and properly trained personnel should use or handle explosives and detonators. Trainees should perform this work only under supervision. Never smoke within 25 feet of the blast area, powder truck or powder magazine.

- Do not leave explosives unattended unless they are placed in a locked magazine. Do not store detonators in the same magazine as explosives. Never store boxes of explosives on their ends or sides, or stack them more than six feet high. Boxes of explosives should be stored at least two inches away from the walls of the magazine. Destroy damaged or deteriorated explosives or detonators safely, under supervision.

- Use only authorized vehicles to transport explosives and off-load all explosives before taking a vehicle to the shop for repairs. Never carry passengers or any other material in the same compartment as explosives. Vehicles and personnel not needed for supervising and charging the blast holes should not be permitted in the loading area. Always use the proper blasting warning signals.

- Lead wires and blasting lines should not be strung across power conductors, pipelines, railroad tracks, or any other objects that can carry current. No loading can be done while a power cable is in the blasting zone. Power cables must be at least 25 feet from the blast area.

- When riding a vehicle, remain seated and use a safety belt while in motion. Never ride on the sides of vehicles, on forks or in the bucket of any equipment. Be sure that the automatic back-up alarm on the vehicle is working properly and can be heard by those working nearby.

- When operating a vehicle, observe all company and state/local traffic regulations. Obey all warning signs, barricades and all traffic control signs on company property. Notify the supervisor of hazardous or unusual conditions that are encountered, such as washed-out roads or limited visibility. In inclement weather, travel and access ways should be sanded, salted or cleared of snow and ice as soon as possible.

- Do not drive above posted speed limits. Slow-moving and light vehicles used at night or on overcast days should be equipped with a flashing amber light that is visible to on-coming traffic. Haul trucks have the right of way over all vehicles, except emergency vehicles and explosive materials trucks. Under normal operating conditions, stay at least 100 feet behind a haul truck on level ground and upgrades, and at least 300 feet on downgrades. Ground personnel should wear high visibility vests. When parking a vehicle, set the parking brake and turn the wheels into the bank.

- When involved in an accident on a public road in a company vehicle, pull off the road if possible. If qualified, give aid to anyone who is injured. Place warning reflectors or flares on the road as needed, and report the accident to the company supervisor and the proper law enforcement agencies as quickly as possible.

- Do not operate any equipment unless trained and authorized to do so. Stand clear of loads being lifted or lowered and never move a load over the top of any person. When operating cranes, be sure there is adequate clearance from all power lines. Check the required boom angle for the load to be handled. Never make lifts in excess of rated capacity.

- MSHA regulations state that fall protection must be worn if there is a potential to fall. A minimum height should be established where fall protection is required to facilitate consistent enforcement. If working overhead, rope off the area below and place warning signs near the area. Raise and lower power tools or materials with a hand line attached to the object. All cranes, hoists or man-crawlers used to raise or lower workers must be fully equipped with over-speed, over-wind and automatic stop devices. Use caution when climbing a vertical ladder. If possible, tie the top of the ladder to a stable, fixed point. Keep both hands free and do not hurry. Inspect the ladder before using it. If a ladder is defective, tag it and remove it from service. Never use defective equipment or tools. Keep one hand free when carrying objects on stairways, allowing for use of the handrail.

- Only authorized personnel are allowed to work on electrical wiring and equipment. Before performing electrical work, be sure that the circuit is de-energized and grounded.

- Do not wear loose, torn or baggy clothing near moving machinery.

- Alcoholic beverages and illegal drugs are not allowed on the job. Working while under the influence of alcohol and illegal drugs is absolutely prohibited. Any use of prescription drugs or over-the-counter medications while working should have the prior approval of a licensed physician or the site management. Many prescription and over-the-counter medications can affect balance and impair the ability to operate machinery.

- Establish a written confined space entry program. All confined spaces, whether permitted or non-permitted, should be identified and marked in advance by safety and health personnel. All employees must observe all regulatory requirements and company procedures for entering confined spaces.

- Be sure that radio transmissions are understood and acknowledged. In case of an emergency, radio communication must be limited to emergency personnel.

Voluntary Consensus Standards

For decades, MSHA and OSHA have utilized national and international voluntary consensus standards in addition to the mandatory standards and guidance materials. In fact, many of OSHA's initial standards were derived directly from 1960s-era safety standards developed by the American National Standards Institute (ANSI), under a special provision of the Occupational Safety and Health Act of 1970.

Where a consensus standard has been incorporated by reference into a mandatory safety and health standard, the requirements of the consensus standard become binding upon the regulated community even though the full text of the standard may not be published in the Code of federal Regulations. Thus, in order to be aware of all compliance obligations, aggregates producers must become familiar with those consensus standards. Voluntary consensus standards also have been relied upon by OSHA for enforcement under its General Duty Clause (Section 5(a)(1) of the OSH Act), because knowledge of these standards is imputed to affected industry groups and such standards often constitute an industry standard of care or define "recognized" hazards.

The primary standard-setting organizations whose works have been incorporated by MSHA and OSHA in mandatory standards include:

- American National Standards Institute (ANSI)
- ASTM International (ASTM)
- Society of Automotive Engineers (SAE)
- National Fire Protection Association (NFPA)
- American Society of Mechanical Engineers (ASME)
- Institute of Makers of Explosives (IME)
- American Welding Society (AWS)
- Institute of Electrical and Electronic Engineers (IEEE)
- National Bureau of Standards (National Electrical Code, or "NEC")
- Underwriters Laboratories (UL)

In addition, MSHA adopted the threshold limit values (TLVs) set by the American Conference of Governmental Industrial Hygienists (ACGIH) as mandatory air contaminant standards. The metal/nonmetal air contaminants standard, published at 30 CFR 56.5001, incorporates the 1973 version of the ACGIH's TLVs. More consensus standards are likely to be adopted by MSHA and OSHA in future rulemaking activities.

The implications of voluntary consensus standards in tort litigation should not be ignored. Because of the broad application of such standards, mine operators must utilize both sound science and technically feasible engineering practices so that they can go beyond minimal regulatory compliance and implement all recognized best practices to protect the safety and health of workers and the public.

6.5 Safety and Health Management Systems

For years, managers in the aggregates industry managed safety as a discrete set of individual, unrelated activities ancillary to the mining operation, most of which evolved as a result of regulatory requirements. Over time, it became evident that a systematic approach to managing safety and health—as a part of the operator's overall management philosophy—was the only sure way to achieve high-level, sustainable performance.

A safety and health management system is designed to function as an inter-related collection of activities and processes that create safe workplace conditions and behaviors among all employees. These in turn reduce accidents and injuries.

A management system is a process control system that is integrated with all other management processes and activities. It is based on the premise that it's possible to control the outputs of an organization—in this case injuries—by managing the processes and events that contribute to those outputs.

The groundwork for such a system was laid by the MSHA-NSSGA Alliance with its 2003 development of the "Core Principles of Safety." These include:

- Front line management leadership and commitment
- Training and development
- Formal auditing of all employee work practices
- Employee involvement and participation
- Incident investigation
- Safety communications
- Regulatory compliance program
- Operational safety best practices
- Accountability and recognition systems
- Substance abuse prevention program

Today, the foundation of many effective management systems is the Plan, Do, Check, Act model wherein each program, procedure or activity within the system is managed in a controllable way to gain the output desired—in this case, workers with no injuries or occupational illnesses.

- "Planning" starts with the highest level of management taking responsibility for their operation's safety and health performance. The management can then:
  - Assign specific safety and health program responsibilities to specific individuals;
  - Identify hazards, risks and regulatory obligations (MSHA, OSHA, DOT, etc);
  - Set realistic objectives;
  - Create the actual safety and risk management procedures and practices;
  - Provide necessary resources to mitigate risks; and
  - Develop the metrics to measure progress in accomplishing the objectives.

- "Doing" involves executing the procedures created during the "planning" stage. It includes:
  - Minimizing or eliminating workplace hazards;
  - Training employees;
  - Communicating hazard information to employees ;
  - Conducting daily workplace inspections;
  - Following safe work practices; and
  - Investigating the root cause(s) of deviations from standards or expectations.

- "Checking" involves measuring and monitoring the program's outcomes by reviewing:
  - Processes Indicators (or "leading indicators") such as the completeness and accuracy of Job Hazard Assessments (JHAs), the timeliness, completeness, effectiveness and relevance of employee training, the number, depth, and effectiveness of audits and accident investigations conducted, etc.; and
  - Performance Indicators (or "lagging indicators") such as the number and severity of incidents, injuries, near misses, property damage, etc.

- "Acting" involves:
  - Improving the original safe-work and hazard-mitigation procedures—based on the results of reviewing the procedures during the "checking" stage;
  - Updating hazard assessment information and knowledge;
  - Providing positive and negative feedback for positive and negative activities; and
  - Making corrections to the overall system where it can be improved.

A key to success in any organization is for individuals to understand their role in the process and how it relates to the overall goal. This is no different in safety and health management. A good safety and health management system assigns responsibilities for safety management to every position in the operation. Although every individual has responsibilities within the management system, those responsibilities may differ greatly depending on each individual's role. A laborer's responsibility might be very different from the senior manager's, but both must clearly understand and be held accountable for their role in the organization's safety and health performance.

The remainder of this chapter will focus on three key applications of a well-designed safety and health management system: 1) occupational health programs; 2) safety management programs; and 3) regulatory compliance, which impacts both safety and health programs.

6.6 Occupational Health

Recognition and Prevention of Occupational Illness

The awareness that certain illnesses were associated with specific occupations has a very long history.[ii] Fortunately, as the awareness of occupational illnesses grew, attempts to prevent them followed. For example, several organizations formed during the first half of the 20th century; these organizations create and publish Occupational Exposure Limits (OELs) for chemical and physical agents.[iii] The limits may be expressed as full-shift limits, short-term limits or ceiling limits.[iv]

The 20th century also brought legislation that provided broader legal backing to protect workers' health. For example:

- The Walsh-Healy Public Contracts Act of 1936
- The Metal and Nonmetallic Mines Safety Act of 1966
- The federal Coal Mine Safety and Health Act of 1969
- The Occupational Safety and Health Act of 1970

OSHA adopted the 1970 ACGIH TLVs as its initial Permissible Exposure Limits (PELs); MSHA adopted the 1973 TLVs for the same purpose. While the TLVs are voluntary guidelines, the PELs are legally enforceable.[v]

6.7 Occupational Health Programs

Advances in science and technology over the past several decades have contributed extensively to the growth and effectiveness of occupational health programs. The accuracy and sensitivity of laboratory analytical methods have improved significantly and now allow the detection of very small quantities of an increasing number of toxic materials.

Industrial hygiene sampling equipment has improved dramatically. Lightweight pumps can collect full-shift air samples; flow-rate calibrators have been greatly simplified; and noise dosimeters accumulate and analyze thousands of data points for a single work shift.

Many workers in the aggregates industry are potentially exposed to a variety of occupational health hazards. Two of the major hazards are respirable crystalline silica and excess noise. Additional concerns may include asbestos, total dust, welding fumes, solvents, temperature extremes, and diesel fumes and particulates. This partial list can be expanded depending on the materials and processes used at a specific site.

- Silicosis is caused by prolonged overexposure to respirable crystalline silica, commonly found in rock dust. Silicosis is a fibrotic lung disease that scars the lungs.

- Hearing loss from excess noise has long been known as a potential consequence of mining. MSHA and OSHA have PELs for noise exposure and both agencies require hearing conservation programs.

- Asbestos is widely recognized as a serious potential health hazard, causing scarring of the lungs (asbestosis), and cancers of the lungs, linings of the chest cavity and abdomen (mesothelioma). The six asbestiform minerals that are or were mined commercially are called "asbestos" and have been highly regulated in the U.S. since the early 1970s and are not, nor ever have been, products mined by the aggregates industry.[vi]

- Welding fume hazards vary widely with the base metal, the welding process and environment (particularly in enclosed or confined spaces), and the composition of the electrodes used.

- The MSHA diesel particulate matter (DPM) standard was published in 2001 to protect underground metal and nonmetal miners from a variety of adverse health effects, including lung cancer. A great deal of controversy exists about the extent of the claimed health hazards, the reliability of the analytical methods and the effectiveness of control measures.

NSSGA Occupational Health Program

Introduction

NSSGA's model Occupational Health Program (OHP) gives Association members and others a template for establishing their own program that can address key occupational health risks in the aggregates industry. NSSGA's safety and health Guiding Principles include the adoption by members of sound industrial hygiene and occupational medical programs to prevent job-related illnesses.

The key elements of an effective OHP include:

- A commitment by the company's senior management;
- An employee communication, promotion and training program;
- An exposure monitoring program;
- An exposure control process;
- A medical monitoring program;
- An emphasis on smoking cessation; and
- A process for periodic evaluation and auditing of the program and acting on the audit findings.

The NSSGA model OHP is not a substitute for the safety and health requirements of insurance companies or federal, state or local regulatory agencies. Individual tailoring by member companies to fit their specific requirements is necessary to make the program most effective for each company.

Management Commitment

A clear and unambiguous commitment by the company's senior management is essential to the OHP's success. Senior management must understand and be committed to the goals and requirements of the OHP. This commitment must include providing the resources to do the job, including personnel, equipment and support services such as analytical laboratory costs. Understanding that an effective OHP is a good business practice will help to secure this commitment.

Communication, Program Promotion and Health Hazard Training

Communication

After management commits to the program, it should be introduced to the workforce. The OHP benefits employees by reducing their risks. The program also should answer the questions: "Have I been exposed to workplace hazards and, if so, have I been affected by the exposures?"

The essence of the OHP can be communicated to employees during a safety and health meeting, and by listing and describing the elements of the OHP. Employees should understand that the purposes of the program are to:

1. Prevent occupational diseases in the future by measuring and controlling exposures;
2. Identify and deal with any existing occupational illness within the employee population; and
3. Refer employees to their personal physicians in the event that symptoms of non-occupational illnesses are identified that the employee may not be aware of.

If the employees work under a collective-bargaining agreement, management should inform union officials of the OHP and solicit their support before introducing it to the employees. When labor relations are not adversarial, it may be beneficial to work with the union leadership during the operator's tailoring of the OHP. Employees can then be assured that the program does not conflict with the agreement. The company's insurance carrier and/or risk management department should be involved as well.

Managers must emphasize that exposure monitoring, such as for dust or noise, is non-intrusive; i.e., no body fluids will be collected or needles used, and employees will be notified of their individual sample results.[vii] Sound, thoughtful preparation is the most certain means to achieving the highest possible level of employee participation and cooperation.

Promotion

The OHP in general, and the medical screening portion in particular, should be promoted in flyers, posters, bulletin board presentations, payroll stuffers, safety and health meetings and toolbox talks. To show management support and interest, every supervisor should take an active role in promoting the OHP. To assure that non-English-speaking employees are included, a special outreach effort should be made for them. Promote the program to employees' spouses, as they may be an effective, personal source of encouragement to the employee. Emphasize the personal benefits of exposure monitoring for silica, noise, fumes and other potential hazards.

Air or noise samples should be collected on a representative group of employees so the company can assess if potentially hazardous conditions are under control. The results of these samples will be shared with and explained to employees, and where possible the company will enlist their support in solving any exposure problems.

Health Hazard Training

Training employees about occupational health hazards is intended to educate them, foster healthful work practices, and kindle their desire to participate in the company's OHP. Training can be an essential line of employee defense against potential hazards when engineering and administrative controls are insufficient. For many occupational health hazards, the biggest hurdle in effective training is gaining employee respect for the risks involved. Because many hazards do not cause immediate evidence of harm, employees often don't realize that they may be at risk at the time they are exposed.

Health hazard training should focus on identification of stressors that could cause injury or illness and emphasize the means of prevention or protection. This training is a fundamental part of the MSHA Hazard Communication Standard. As previously stated, potential health concerns in many aggregates mining environments often include the following:

- Respirable silica
- Excess noise
- Welding/cutting fumes
- Solvents and degreasers
- Diesel exhaust
- Temperature extremes
- Confined spaces
- Other health hazards unique to the operation

Resources and reference materials for training purposes are available through the following websites:

- MSHA (www.msha.gov)
- OSHA (www.osha.gov)
- NIOSH (www.cdc.gov/niosh)
- NSSGA (www.nssga.org)

Exposure Monitoring Program

Exposure monitoring (employee sampling) is generally the most practical and effective way to assess employees' exposures to dust, noise, welding fumes and other potential health hazards. Operators' occupational health programs often determine the type and frequency of exposure monitoring. Other conditions or events that may prompt exposure monitoring also include:

- MSHA and OSHA regulations;
- Comments or complaints from employees;
- Observations or qualitative exposure assessments;
- Results of medical examinations or tests;
- Worker's compensation claims that indicate possible overexposure conditions; and
- The introduction of new production procedures or work duties with unknown exposures.

Pre-Monitoring Activities

Several tasks must be completed before actual monitoring begins: selecting and training individuals who will conduct the monitoring, selecting an analytical laboratory, determining the type of monitoring equipment to use, evaluating the exposures that need monitoring, and determining which employees, areas and dates/times to monitor.

Individuals who will conduct sampling must be competent in the assessment of exposure risks, the use of sampling equipment and the analysis of data.[viii]

Choose a laboratory that is accredited by the American Industrial Hygiene Association (AIHA); the laboratory must participate in the AIHA Proficiency Analytical Testing (PAT) program for the substances being analyzed.[ix]

When selecting monitoring equipment, consider the flow capacity, run time, size and weight of the equipment. Also consider the environment in which the equipment will be used; temperature extremes, the presence of excess dusts and liquids, or rotating equipment and other factors may restrict the full use of equipment.

A great deal of information should be gathered prior to sampling to determine sampling needs and priorities. Ideally, this information is captured in the Job Safety Analysis (JSA) process.[x] The information can be gathered through observation during site walkthroughs, record review and employee interviews. Helpful records include exposure information from similar work tasks and operations and the mineralogy of the mine deposit. During a walkthrough of the plant, the operator should estimate risks generically based on the nature of the process, how close employees are to exposure sources and the amount of time they spend there, the number of workers potentially exposed, the effectiveness of existing controls, and employee complaints or claims due to exposures.

Note specific contaminants that are common to the industry during your walkthrough. For respirable crystalline silica, the operator should observe the amount of settled dust on and around equipment, significant dust on workers' clothing and dust in the air. Note that respirable dust is invisible; hence, the absence of visible dust does not necessarily mean that respirable dust is not present.

For welding/cutting operations, particularly those indoors or in enclosed spaces, the operator should ascertain the types and quantities of welding rods present, types of welding or cutting performed and whether welding fume portable exhaust systems are present and in use.

Sampling Activities

Conduct sampling to determine and document:
1. Compliance with regulatory and company standards;
2. If additional control measures are needed; and
3. The effectiveness of existing controls.

Sample data are useful in addressing management and employee concerns and to establish a database of exposure history for the site. This history can be used to evaluate the relationship, if any, between exposures and adverse health responses.

Most exposure monitoring involves personal sampling. Monitoring equipment is attached directly to the employees for the duration of the work shift. This technique is the best method to estimate a worker's unique exposure to a particular substance.[xi]

Area samples measure concentrations of substances at a specific location, as opposed to a specific person. Area sampling can help to determine which job tasks contribute most significantly to an employee's total exposure. Area sampling also can identify areas that require personal protective equipment. However, area sampling is not a substitute for personal monitoring and it is not recognized as such by MSHA or OSHA.

Exposures that exceed the appropriate OEL must be tracked until they are resolved through hazard elimination, product substitution or hazard controls (e.g., engineering controls, administrative controls and/or personal protective equipment use). Once controls have been installed, re-sampling should be conducted to demonstrate that the controls work as intended.[xii]

Once the Targeted Sampling Strategy has revealed any excess exposures and the needed controls have been installed (and determined to be effective), the next step is to implement a Random Sampling Strategy.

Random sampling supports statistical decision making. The appropriate analysis quantifies the probability of excess exposure throughout the entire workforce or for any portion thereof. In random sampling, every employee at a site or in a given group (such as job classification or work area) should have an equal chance of being selected for sampling.[xiii]

Data from random sampling provide crucial information for future epidemiological studies and defense against any future claims.

Post-Sampling Activities

Employees must be notified of their own sample results in a timely manner and in compliance with regulatory requirements. This is an excellent opportunity to help employees understand the Occupational Health Program (OHP); it also may enlist their cooperation with any necessary exposure control efforts.

Exposure data management and record retention are essential elements of the OHP. For exposure data to be most useful, records should be accessible by a number of variables, such as site, employee, job sampled, mobile equipment, mine area, sample date, substance monitored, exposure levels, etc. It is necessary to computerize large amounts of exposure data.[xiv]

Exposure Control Process

The Exposure Control Process (ECP) is a uniform method for correcting and controlling work-related exposures to chemicals and physical agents that could affect the health of employees. In the practice of industrial hygiene, a hierarchy of controls exists that emphasizes feasible engineering controls as the most reliable since they don't depend on human behavior to be effective when installed and maintained properly. When engineering controls are not feasible, or when they are being installed or are shut down for maintenance purposes, employees should be protected by administrative controls and, as a last resort, personal protective equipment (PPE). Many regulations mandate this hierarchy of controls to achieve compliance.

The design and installation of controls is generally the responsibility of line operating and maintenance personnel.

Proactive control strategies anticipate potential adverse exposure conditions based on hazard awareness. Control strategies (and examples) include:

- Elimination of the hazard (removing a particular chemical from the workplace)
- Substitution of a less hazardous substance (using a chemical with less hazardous properties)
- Engineering Controls (plant design and engineering/construction that minimizes exposure to hazards)
- Preventive maintenance on existing controls
- Administrative controls (scheduling maintenance work when equipment is not operating)
- Use of PPE when other controls are insufficient or infeasible, or during emergencies.

Sampling technicians and health and safety professionals usually collect and interpret exposure sample results and communicate the findings (frequently with options for exposure controls) to those responsible for taking appropriate action.

Any unacceptable exposure conditions and the possible causes of such exposures should be communicated in writing to the responsible operating management. Operators should include any recommended exposure controls, and inform affected employees of the excess exposure condition in writing with a clear explanation and meaning of the results.

Overexposure conditions should trigger an Exposure Control Plan that involves input from the employees, where possible. In turn, employees should acknowledge in writing that they received and understand the potential consequences of their exposures. After proper training and fitting, PPE must be used by affected employees until feasible engineering and/or administrative controls are in place and subsequent sampling demonstrates that the exposure does not exceed the OEL. Employees should continue to use appropriate PPE when working at tasks or in areas where exposures cannot be fully controlled by engineering and administrative controls.

Medical Monitoring Program

A company's medical monitoring program (MMP) should include periodic medical evaluations that can detect job-related medical conditions or symptoms at an early stage, when corrective measures can be most beneficial. The evaluation may also detect non-occupational health conditions in their early stages, which may result in more effective treatment. Moreover, by contributing appropriately censored employee health data to epidemiological research, an employer's MMP can help ascertain if a possible cause and effect relationship exists between the exposure and any health conditions detected.

Employees who are enrolled in an MMP should initially receive a baseline medical evaluation. Baseline evaluations are important for use in assessing future changes.

Quality medical testing and interpretation of test results is paramount. Diagnostic testing requires appropriate equipment and qualified health care personnel to conduct, supervise and interpret these tests.

Due to potential dust and noise conditions in many aggregates operations, the medical testing program typically emphasizes the employees' respiratory and auditory systems.[xv] However, the program should be tailored to the specific exposures that may be encountered in a given operation.

A medical and personal history is an important part of the MMP and may detect potential health problems that require further evaluation. The work history is needed to define previous potential exposures to hazardous materials. A work exposure history should include, as a minimum:

- A complete list of all previous jobs and materials to which the employee was exposed;
- Whether a respirator or hearing protection was worn on the job;
- Military service; and
- Hobbies or activities that may have exposed the worker to hazardous materials or high noise levels.

Other considerations of an MMP include the following:

- Medical and exposure records should be retained for the length of employment plus at least 30 years thereafter. All medical records must be maintained in accordance with the Health Insurance Portability and Accountability Act (HIPPA) of 1996.

- All non-occupational health problems detected by the MMP should promptly be referred to the individual's health care provider.

- Evaluations that help establish whether an employee or prospective employee is physically capable of performing the essential job functions are often conducted at the time of hire and may be distinct from the MMP.

Smoking Cessation Program

According to the American Lung Association (ALA), smoking is directly responsible for 87 percent of lung cancer cases and most cases of emphysema and chronic bronchitis. More than 392,000 people die in the U.S. each year due to tobacco-related diseases, including chronic obstructive pulmonary diseases, certain cardiovascular diseases and other adverse health effects. Moreover, smoking magnifies the insult from exposure to many other agents, particularly asbestos.

It's been estimated that 30 to 40 percent of the aggregates workforce smokes tobacco. As a result, this group experiences an excess incidence of lung cancer compared with the general population (fewer than 25 percent of who smoke). This is important for at least two reasons:

- The excess of tobacco-related disease among miners robs their families, friends and coworkers of valuable relationships, deprives their families of financial support, denies their coworkers and employers of valuable job experience and increases medical costs across the board.

- Several organizations have classified occupational overexposure to respirable crystalline silica as a known lung carcinogen. This means that tobacco-related lung cancer among aggregates miners may be attributed instead to silica exposure, which confuses the medical research and may lead to unnecessarily stringent and unhelpful regulations.

The impact, therefore, of smoking on productivity, absenteeism, workers' compensation and the health care system is staggering. Clearly, there is an urgent need for employers to encourage employees to stop smoking. An effective smoking cessation program is a means to that end.

Smoking cessation programs range from simply educating employees on the hazards and consequences of smoking to counseling and support groups, medical treatment and providing compensation or other incentives for quitting. The Internet and telephone quit-lines provide low-cost and barrier-free access to information and counseling, heightening optimism that the effects of this health problem can be minimized. Available Internet resources include:

- National Cancer Institute: www.smokefree.org
- Wellness Web: www.wellweb.com (medical information and support)
- American Lung Association: www.lungusa.org/stop-smoking/Mayo Health Clinic: www.mayoclinic.com/health/quit-smoking/MY00433
- Foundation for Innovations in Nicotine Dependence (FIND): www.findhelp.com
- Professional Assisted Cessation Therapy (PACT): www.endsmoking.org
- National Business Group on Health: www.wbgh.org/tobacco/

Process Evaluation and Auditing

To assure its ongoing effectiveness, the OHP must include an evaluation and auditing function. A set of measurable performance criteria with time lines and priorities should be established early in the OHP's development. Appropriately trained personnel should periodically evaluate these criteria for each section of the OHP, with the results reported to senior management. Management must assign responsibility and provide the necessary resources to address any program variances in a timely manner.

Summary

Modern aggregates facility operators who take steps to ensure worker safety and health are nonetheless under increasing pressure from the public and regulatory agencies to reduce accidents and injuries. The best way to accomplish this objective is to develop and effectively implement a comprehensive, written safety and health program. Contractors should be required to have and follow a similar written safety and health program for their employees who work on facility property.

APPENDICES

History of Federal Safety Legislation

Federal mine safety concerns date back to 1865, when a federal mining bureau was established. A series of mine disasters shortly after the turn of the century stimulated the enactment of meaningful federal legislation. In 1910, Congress established the U.S. Bureau of Mines within the Department of the Interior, and charged the bureau with investigating mining methods relating to miner safety, accident prevention and the use of explosives. While this act acknowledged a need to reduce the hazards associated with coal mining, the U.S. Bureau of Mines' employees were specifically prohibited from inspecting or supervising mine operations.

The 1936 Walsh-Healey Public Contracts Act was among the earliest federal attempts to regulate occupational safety and health in the private sector (applying to U.S. government contractors whose business with the government exceeded a specific dollar value). Beginning in 1968, Walsh-Healey adopted the ACGIH TLVs as enforceable OELs. Walsh-Healy standards were absorbed into many of the subsequent federal regulations.

In 1941, the federal Coal Mine Health and Safety Act was enacted. This act gave the U.S. Bureau of Mines the authority to inspect underground coal mines and publicize its findings and recommendations, but provided no provision for establishing safety standards or achieving compliance with any recommendations or regulations.

In the late 1940s, Congress required coal mining companies and state mining agencies to report the degree to which compliance was being achieved with a federal Mine Safety Code developed cooperatively by the Department of the Interior and the mine workers union. This congressional effort, which was an information gathering piece of legislation, found only 33 percent compliance with the U.S. Bureau of Mines' recommendations. Repeated efforts in Congress in 1952 and again in 1966 resulted in giving the U.S. Bureau of Mines, for the first time, the necessary legislation that enabled inspectors to prevent certain types of repeated safety violations in coal mines.

In 1966, the first federal act was passed affecting the nation's non-coal mines, including crushed stone quarries, and sand and gravel pits. The federal Metal and Nonmetallic Mine Safety Act of 1966 established, within the U.S. Bureau of Mines, the Mine Enforcement Safety Administration (MESA). This law directed MESA to develop specific mandatory safety regulations designed to reduce the number and severity of pit- and quarry-related injuries and granted MESA on-site inspection authority. Regulations under the act went into effect in 1970. The federal Coal Mine Health and Safety Act of 1969 provided a similar, but more punitive, regulatory scheme for the nation's coal mines. The 1969 Coal Act provided for civil penalties for violations of safety and health standards while the Metal and Non-metal Act did not. The standards established under the Coal Act were mandatory, while those developed under the Metal and Nonmetal Mine and Safety Act were often advisory in nature.

The Mine Safety and Health Administration (MSHA) was created in 1978 as part of the federal Mine Safety and Health Act of 1977, Public Law 91-173, as amended by Public Law 95-164. Under this law, MSHA was given significant powers and responsibilities, including a mandate to inspect each surface mine in its entirety at least twice per year and inspect each underground operation at least four times annually.

In addition, the National Institute for Occupational Safety and Health (NIOSH) has a role in informing MSHA regulatory decisions and in conducting research on mine health and safety issues. NIOSH personnel, like MSHA inspectors, have the right to enter mines in order to carry out their responsibilities under the Mine Act. NIOSH, which is part of the Centers for Disease Control and Prevention within the U.S. Department of Health and Human Services, has assumed the research and consultation role that was previously maintained by the U.S. Bureau of Mines. NIOSH maintains a branch dedicated to mine safety and health, with research facilities in Pittsburgh, Pa., and in Spokane, Wash. The NIOSH mining resources website appears at www.cdc.gov/niosh/mining/.

MSHA's authority to conduct warrantless inspections was upheld following a legal challenge in Donovan v. Dewey, 452 U.S. 594, 604-05(1981). MSHA can seek injunctive relief, in the U.S. District Court, to enforce its right of entry under Section 103 of the Mine Act if a mine operator attempts to prevent an inspection or mine investigation.

The Mine Act is a strict liability statute, which severely limits the defenses that a mine operator can offer when disputing MSHA citations or the associated civil penalties. When the Mine Act was first enacted, civil penalties were capped at $10,000, but this was later increased and indexed for inflation. The U. S. Congress enacted the Mine Improvement and New Emergency Response Act of 2006 ("MINER Act" Public Law 109-236), which directed the agency to increase maximum penalties to $220,000 per flagrant violation. The statutory provisions are published at 30 USC 801 et seq., and health and safety standards promulgated by MSHA are codified at 30 CFR 1-199.

Legislation of Importance to the Aggregates Industry

In 1977, Congress enacted the federal Mine Safety and Health Act, 30 USC 801 et seq. ("Mine Act") which replaced both the 1969 Coal Act and 1966 Metal and Nonmetal Mine and Safety Act. This legislation dissolved the Mining Enforcement Safety Administration (MESA) that was under the U.S. Department of the Interior, established MSHA within the U.S. Department of Labor, and directed NIOSH to enforce mine safety and health regulatory decisions and conduct research on safety and health hazards affecting miners. The Mine Act and its successor legislation give MSHA full regulatory authority over all mines in the United States, including surface and underground crushed stone quarries, cement plants, and sand and gravel pits.

As discussed above, this legislation was updated in 2006 by the MINER Act, which enhanced MSHA's penalty system and injunctive powers, as well as mandating additional protections for underground miners in terms of communications, respiratory protection and mine rescue teams.

Federal Interagency Agreements

The federal Occupational Safety and Health Act, which went into effect in the early 1970s, established OSHA within the U.S. Department of Labor. In this Act, OSHA was given jurisdiction over safety and health concerns at most workplaces throughout the United States. With the establishment of MSHA within the U.S. Labor Department, it was felt that better coordination could and should be achieved between MSHA, which has jurisdiction over safety and health at mine operations, and OSHA, which oversees safety and health at the support facilities such as maintenance shops, offices, etc.

To eliminate potential jurisdictional disputes, MSHA and OSHA entered into an interagency agreement on April 17, 1979, to delineate areas of authority and provide for coordination between the two sister agencies. This agreement established MSHA's authority to regulate the working conditions of employees engaged in underground and surface mineral extraction and related operations, and also in the preparation and milling of extracted minerals. The following types of operations are excluded from MSHA's authority and thus are regulated by OSHA: gypsum board plants; brick, clay pipe and refractory plants; ceramic plants; fertilizer production facilities; asphalt mixing plants; concrete ready-mix or batch plants; custom stone finishing; smelting; electrowinning; salt and cement distribution terminals not located on mine property; refining; and surface oil shale retorting. Despite this agreement, in recent years MSHA has asserted its authority over some operations, such as asphalt plants and equipment repair shops, based upon whether miners are exposed to hazards at these facilities because the plant is co-located at a mine site, or whether the operation engages in activities, such as milling, crushing and screening of minerals, which would bring the work under the purview of MSHA. The federal Mine Safety and Health Review Commission regularly considers jurisdictional cases where there is a dispute over whether OSHA or MSHA have legal authority over a particular facility.

MSHA also entered into an interagency agreement with the U.S. Treasury Department's Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) to perform, on behalf of ATF, inspections of explosives storage facilities at MSHA-regulated facilities and inspect the records required at the storage site. In addition, MSHA became responsible for establishing safety standards for the transportation, storage, and use of explosive materials at mining operations. ATF, however, continues to make inspections and investigations of applicants for licenses and permits.

In the wake of 9/11, Congress enacted stronger controls on explosives, directly affecting the mining industry. The Safe Explosives Act, Public Law 107–296, was signed into law on November 25, 2002, and took effect in 2003. The SEA enhances federal license and permit requirements, background checks, provides for increased site inspections, adds new paperwork requirements, and restricts the categories of persons who may lawfully receive or possess explosive materials. In the event of lost or stolen explosives, ATF has the statutory right to examine the permanent records of federal explosives licensees and permittees without a warrant under 18 U.S.C. 843(f).

U. S. Mine Safety and Health Administration

MSHA is authorized by law to develop and distribute information, and to develop and enforce mandatory minimum safety and health standards for the protection of life and prevention of injuries in coal or other mines including surface pits and quarries. Following enactment of the Mine Act, safety and health standards for surface and underground aggregates operations were promulgated and today are published in 30 CFR Part 56 (surface) and Part 57 (underground), while abrasive blasting and drill dust control standards are found in Part 58.

In addition, MSHA developed specific training requirements for surface aggregates and cement facilities, which took effect in 2000 (30 CFR 46). Underground training for all types of mining is specified in 30 CFR 48. Other significant regulations, applicable to all mining operations, include MSHA's hazard communication standard (30 CFR 47), recordkeeping and reporting requirements (30 CFR 50), and noise protection (30 CFR 62). Mine operators can petition for modification of safety standards under certain conditions and the procedures for such petitions are governed by the rule in 30 CFR 44. MSHA's civil penalty system is prescribed in 30 CFR 100, while the agency's "Pattern of Violations" program is outlined in 30 CFR 104.

Each proposed new regulation issued under the Mine Act and its successor statutes is published in the *Federal Register* and, in accordance with the Administrative Procedure Act, public comments are accepted before the rule (or standard) becomes final. If, as sometimes occurs, the regulated industry or its unions disagree with the final rule, the Mine Act provides for judicial review of the standard in the U.S. Court of Appeals, with the potential for final review by the United States Supreme Court. MSHA must provide a copy of each proposed standard to every mine operator at the time of publication. The operator, in turn, must post a copy of every proposed standard on the bulletin board of the mine. Copies of all proposed and final rules, testimony from public hearings and public comments that have been submitted, as well as the current regulations in the Code of federal Regulations, also are published on MSHA's website at www.msha.gov.

Generally, the MSHA standards cover such areas as ground stabilization; fire prevention and control; air quality, chemical substances, and respiratory protection; explosives; drilling; loading, hauling, and dumping; aerial tramways; travelways; electricity; compressed air and boilers; machinery and equipment; personal protection; materials storage and handling; illumination; safety programs and personnel hoisting.

Other Agencies Affecting Mine Safety and Health

Although MSHA has primary jurisdiction over mine safety and health, with additional roles for NIOSH and ATF as discussed in more detail above, there are a number of other federal and state entities that have authority to conduct investigations or regulate certain activities that may occur on mine property or arise from mining activities.

Preeminent among them is the U. S. Environmental Protection Agency, which is discussed elsewhere in greater detail. Whistleblower protection provisions in many environmental statutes that are applicable at mine sites are investigated and enforced by OSHA, despite MSHA having general enforcement jurisdiction at such facilities.

In addition, in some states (e.g., California), the state-plan "OSHA" agency may have concurrent jurisdiction at mine sites and can enforce its own safety and health standards in addition to the enforcement actions of MSHA. Thus, an operation in California that has an incident involving a safety and health violation may receive citations and monetary penalties from both MSHA and from Cal-OSHA.

At the federal level, the following agencies also play roles in mine safety and health:

- Federal Railroad Administration: This agency has authority over rail operations and track conditions where they may cross mine property. The federal Railroad Safety Act, enacted in 1970, resulted in myriad regulations addressing railroad installation, maintenance, inspection and repair. Civil and criminal penalties may be imposed upon mine operators who operate rail facilities and who fail to adhere to FRA rules.

- The U.S. Department of Transportation: This agency regulates commercial drivers and imposes commercial driver's license requirements for operators of large trucks that may perform work on and off the mine site (e.g., haulage of aggregates materials from the mine to construction sites). The DOT has hours of service rules for commercial drivers and mine operations that employ drivers with a commercial driver's license (CDL) will be subject to these limitations. Whistleblower protection laws for CDL drivers employed by mines are enforced by OSHA.

- Chemical Safety and Hazard Investigation Board (CSB): The Board is an independent agency that investigates chemical incidents at commercial and industrial facilities, including aggregates mines. It has not enforcement or regulatory authority but produces detailed investigative reports that are publicly available at the Board's website (www.csb.gov). To come within the purview of CSB investigations, an incident must involve a chemical release, at least one fatality or serious casualty, property damage greater than $250,000 and workplace or community evacuation.

- National Transportation Safety Board: The NTSB may investigate incidents that occur on mine property. It investigates incidents involving rail transportation, certain over-the-road trucking operations, pipeline accidents, marine accidents and all civil aviation accidents.

- U.S. Coast Guard: The Coast Guard has jurisdiction over navigable waterways that pass through mine property as well as certain dredging operations and those involving shipping aggregates materials to docks at mine sites. The Coast Guard and MSHA agreed to cooperate and MSHA generally regulates vessels that would otherwise be uninspected under Coast Guard regulations (e.g., small boats used for transportation within mining facilities).

Inspections, Citations and Recordkeeping

The federal Mine Safety and Health Act requires that MSHA inspect each surface mine including all pits and quarries at least twice annually and each underground mine at least four times a year. Operators may not deny entry to the mine by federal inspectors. If during an inspection MSHA believes that an operator has violated the act, or any MSHA standard, a written citation can be issued to the operator. The citation describes the nature of the alleged violation and sets a time limit for correction of the hazard. The violation or hazard must be corrected within the time set by MSHA or the citation must be appealed.

MSHA has Conference and Litigation Representatives (CLRs) who have conducted initial informal conferences that precede the litigation phase.[xvi] Informal conferences must be requested by the mine operator within 10 days of the issuance of the citation or the right is deemed waived.

Citations issued to a mine operator may be contested before an Administrative Law Judge (ALJ). The federal Mine Safety and Health Review Commission (FMSHRC), which consists of five commissioners, is an independent agency established by the act. This commission employs the ALJs, who hear evidence and make decisions on most issues about enforcement of the act. The FMSHRC can decline to review a case, in which instance a mine operator has review as a matter of right before the U.S. Court of Appeals, D.C. Circuit, or in the circuit where the facility is located.

Less serious cases, involving minimal penalties and no novel questions of law, often are assigned to the Alternative Case Resolution Initiative (ACRI) process, where MSHA CLRs, who are not attorneys but who have training on mine safety and health laws, will represent the agency before the ALJs and FMSHRC. The same process is followed for hearings involving a CLR, and the same rules of procedure largely apply. Commission rules are published at www.fmshrc.gov.

All uncontested or affirmed citations carry civil penalties that vary according to the severity of the infraction. Current penalties, however, cannot exceed $60,000 for each violation, although the MINER Act directs MSHA to increase maximum penalties to $220,000 per violation.

Operators also may be subject to criminal penalties for willful violations, false representations or documentation, training fraud or refusal to comply with orders issued by MSHA.

All accidents, as defined at 30 CFR 50.2(h), that occur on mine property must be investigated by the operator and records of such accidents must be maintained and made available to MSHA and the appropriate state agency. Regardless of whether or not any accidents or injuries occur, each operator must submit a quarterly report to MSHA documenting the number of man-hours worked and all pertinent accident statistics. Accidental injuries or illnesses that are not immediately reportable must still be recorded on MSHA Form 7000-1, and submitted to the agency within 10 days of occurrence. Any incident that is deemed "immediately reportable" under 30 CFR 50.10 will require notification of MSHA within 15 minutes of occurrence, or the mine operator will be subject to a mandatory minimum penalty of $5,000.

If a mine operator is found to have a high number of serious infractions in a specific area (e.g., equipment defects), MSHA may issue a notice that the facility is being considered for placement under a "Pattern of Violations" pursuant to 30 CFR 104. The operator must meet with the appropriate district manager, develop a plan to avoid further safety violations and implement corrective actions. If this is not satisfactory and the mine is placed under Pattern of Violations, any further citations will serve as closure orders for the mine until the situation is rectified.

Individual Penalties

MSHA occasionally conducts "special investigations" pursuant to Section 110(c) of the Mine Act. These investigations target management agents, officers and directors who engage in aggravated conduct exceeding ordinary negligence, and may lay the groundwork for criminal prosecutions under the Mine Act. These individual prosecutions occur where MSHA believes the person failed to prevent violations by his employees (or those of another company, if the workers were under the supervisor's direction or control), or if MSHA alleges that the supervisor/agent knew or should have known of the violative behavior. These individual civil penalties can reach $60,000 per violation—in addition to any penalties assessed against the company—and may be adjudicated separately from any actions taken against the employer for such "flagrant violations." Usually special investigations arise following issuance of citations and orders issued pursuant to Sections 104(d) and 107(a) of the Mine Act, or as a result of denial of entry to the mine in violation of Section 103(a) of the Mine Act, where such citations/orders are classified as involving "high" negligence or "reckless disregard" for a mandatory standard. Where an agent of the company is directly involved in the violative action, or should have taken preventative action, he or she will be deemed to have engaged in "aggravated conduct exceeding ordinary negligence" and will be subject to Section 110(c) prosecution.

All high negligence Section 104(d) and Section 107(a) citations and orders are reviewed for criminal prosecution by MSHA headquarters. Criminal prosecutions are conducted, however, by the U.S. Department of Justice. Criminal prosecutions can be triggered by advance notice of inspections and by knowing and willful violations of mandatory safety and health standards.

The most severe criminal provision is found at Section 110(f) of the Mine Act, which provides a prison sentence of up to five years (a "Class E" felony) for any person who falsifies or alters documents required to be kept under the Mine Act. Although this is most commonly invoked with respect to the Form 5000-23 (records of Part 46/Part 48 training), it also applies to such things as workplace inspection reports, examination of hoists and cranes, roof support inspection in underground mines, and electrical testing records. In addition to incarceration, Section 110(f) provides for a criminal fines, recently increased under the MINER Act, and it is subject to enhancement through application of 18 U.S.C. § 3571, which increases fines against individuals to $250,000, and fines against corporations to $500,000.

Part 46 Training Requirements

30 CFR 46 became effective in October of 2000. The goal of Part 46 is to improve the safety and health of miners by requiring training programs that focus on the health and safety aspects of assigned tasks, so every job can be performed the correct way and so hazards could be recognized and avoided.

Part 46 is the provision that requires training, and retraining of miners of several materials, including sand, gravel and stone. A training plan must be documented and include at minimum training of new hired miners, newly experienced miners, annual refresher training, site specific training and new task orientation training. The training plan also must be implemented properly, by using appropriately trained personnel and methodology to ensure quality training.

Part 46 requires that new miners received at least 24 hours of training or an experienced miner must observe them until this training is completed. In addition, there are training requirements for newly hired "experienced miners" so they may become accustomed to their new work surroundings, procedures, and safety and health risks and hazards. Also, you are required to provide any miner who is encounters a new task (that he/she has no work experience with) to be trained on the health and safety aspects of that task, information about the physical and health hazards of chemicals in the miner's work area, and PPE the miner must wear to adequately protect themselves. For all miners, annual refresher training must be conducted. Part 46 requires that training be conducted during normal working hours and that attendees be paid at their normal rate during this training. Attendees also are to be reimbursed for any traveling expenses, if they are required to travel for the training outside of their normal workplace.

In addition to a company's miners, contractors and/or internal employees (with responsibilities other than mining) must be trained on site-specific hazards. This training addresses the hazards and risks a person could be exposed to at the specific facility where they are working, as well as company emergency procedures.

Hazard Communication

In September 2002, MSHA established 30 CFR 47 to reduce injuries and illnesses related to the use and storage of chemicals in the mining industry. Hazard Communication (HAZCOM) is the standard that requires operations to evaluate the potential hazards of the chemicals they produce, or use, and to be transparent to their employees in regards to these hazards. Mining operations must have a training program, a written hazard communication program, must label their containers of hazardous chemicals and provide access to material safety data sheets (MSDSs). HAZCOM is intended to increase miners' understanding of hazard identification and assessment, and to encourage use of personal protective equipment. OSHA has aligned the HAZCOM standard with the United Nations' Globally Harmonized System of Classification and Labeling of Chemicals. It is unclear how MSHA will adjust its regulation.

Material Safety Data Sheets (MSDSs)

As part of the HAZCOM regulation, miners must have access to MSDSs of chemicals that are used and/or stored at the facility in which they are working. A MSDS is a reference document, which typically is prepared by the manufacturer of the material. The MSDS describes the physical and chemical properties, its hazards (e.g., LD50, ecological toxicity, NFPA rating), and recommended precautions for handling (e.g., PPE), storage, and disposal. The MSHA website (www.msha.gov/msds.htm) provides access to a variety of chemical hazard information.

Miners' Rights and Responsibilities

The 1977 federal Mine Safety and Health Act provides miners with certain rights, including:

1. Having an employee representative accompany the federal inspectors during an inspection at the mine;
2. Initiating an inspection of a mine when reasonable grounds to do so exist such as a violation of the Act, the presence of an imminent danger, or the violation of a safety or health standard;
3. Receiving pay during certain periods of time when a mine has been closed because of a withdrawal order;
4. Being protected from discrimination based on the exercise of rights given by this Act;
5. Receiving appropriate safety and health training; and
6. Being informed of and participating in enforcement and legal proceedings under the Act.

Effect on State Laws

By law, the act may not supersede any state law unless such law is in conflict with the act or any other mandatory health or safety standards. As with other federal standards and regulations, states have the option of establishing and enforcing regulations that are at least as stringent as those on the federal level. Indeed, states may establish more stringent safety and health standards than those enforced by MSHA.

Pit and quarry operators should maintain an up-to-date reference library on safety and loss prevention. The operator could begin by assembling a basic set of selected references and, if desired, expand the library to a more extensive collection. [1-69]

Footnotes

i. Beginning in the early 1800s, Portland cement and asphalt concrete were developed, creating a demand for high quality aggregates. Later, the proliferation of affordable automobiles prompted the need for smooth, all-weather, paved highways. These developments provided the initial stimulus that ultimately transformed the fledgling aggregates industry into the largest, non-fuel-mining industry in the U.S. The erratic World War I economy and lack of priority for highways and construction led in 1915-1918 to the organization of national trade associations within the construction and construction materials sectors. Indeed, the need to reduce mine related disabling worker accidents was one of the major issues leading to the establishment of national aggregates associations. The nation's transition from a wartime economy to the rapid growth of the 1920s required large increases in aggregates production. Regrettably, the frequency and severity of pit- and quarry-related accidents also increased during this period.

ii. Hippocrates wrote about lead toxicity in the mining industry as early as the fourth century B.C. Health risks of working with lead, zinc, sulfur, asbestos, mercury ore, and silica were described by Pliny the Elder in the first century A.D. A pamphlet published in 1473 by Ulrich Ellenborg described occupational diseases of gold miners and the adverse effects of exposure to lead, mercury and carbon monoxide. Paracelsus included a description of miners' lung diseases in a treatise that he authored in the early 1500s. In De Re Metallica, published in 1556, Georgius Agricola described diseases of miners, particularly silicosis. Bernardo Ramazzini published the first comprehensive text on industrial medicine in the early 1700s; it contained descriptions of occupation diseases—including silicosis—that were prevalent among miners at the time.

iii. In 1938, the American Conference of Governmental Industrial Hygienists (ACGIH) was founded as a professional association of industrial hygienists and practitioners of related professions. ACGIH quickly began developing guidelines to limit occupational exposures to harmful materials and workplace conditions (e.g., heat stress and noise). The guidelines, called Threshold Limit Values (TLVs), were first published in 1946. TLVs are occupational exposure limits described by ACGIH as levels to which it is believed a worker can be exposed day after day for a working lifetime without adverse health effects. ACGIH also establishes and publishes Biological Exposure Indices (BEIs) which are relevant to occupational chemical substances measured in an employee's blood or urine (not used for illicit drug testing purposes). "TLV" and "BEI" are registered trademarks of the ACGIH.

The American Industrial Hygiene Association (AIHA) was established in 1939 to further the "recognition, evaluation and control" of occupational exposures and other stressors. AIHA publishes OELs that include WEELs (Workplace Environmental Exposure Levels); and ERPGs (Emergency Response Planning Guidelines) which are estimates for concentration ranges "where a person may reasonably anticipate observing adverse effects as a consequence of exposure to the chemical in question." "WEEL" and "ERPG" are registered trademarks of AIHA.

In 1959, the American Board of Industrial Hygiene (ABIH) was founded to certify individual industrial hygienists (CIHs) and, later, Certified Associate Industrial Hygienists (CAIHs). "CIH" and "CAIH" are protected trademarks of ABIH and the use of these designations is restricted by certain statutes.

iv. Full-shift limits typically apply to an employee's average exposure over his or her full work shift. Short-term exposure limits, often called STELs, are intended to limit an employee's exposure during any 15-minute or 30-mintue work-shift period in which exposures are likely to be the highest. So called "ceiling limits" should never be exceeded during the employee's work shift. Other OELs are based on different time schemes (e.g., the AIHA ERPGs are one-hour exposure levels).

v. Permissible Exposure Limits (PELs) are now established by federal regulatory agencies such as OSHA and MSHA in accordance with the federal Administrative Procedure Act, which requires formal notices of proposed rulemaking and the opportunity for public comments. Initial PELs were adopted from a variety of then-current consensus standards created by ACGIH and ANSI.

vi. Confusion between true asbestos and those nonasbestiform minerals with the same mineral composition has become a significant regulatory challenge. The nonasbestiform minerals, which have not been shown to have asbestos-like health effects, occur widely throughout the U.S. and their attempted inclusion as regulated substances in asbestos standards or legislation has a profound impact on the aggregates industry.

vii. The medical testing element of the OHP could generate employee concern. To allay any misgivings and to abort potential rumors, the workforce should be assured that drug or other substance abuse testing is not part of the program. Make clear that employees with medical abnormalities will not be discharged. However, since an employee who is found to have a health problem may need to be reassigned, the operator should be prepared to address this issue to the employees' satisfaction should it arise. Explain that the medical part of the program will be run under the direction of licensed health care professionals, who will retain all information in strict accordance with the requirements of medical confidentiality while providing the company with only the information necessary to protect employees from harm.

viii. Competency can be gained through past experience, successful completion of an NSSGA/MSHA joint Noise and Dust Sampling workshop or equivalent classroom training, and field instruction conducted by an industrial hygienist. A list of industrial hygiene consulting firms is available through the American Industrial Hygiene Association (www.aiha.org).

ix. For example, X-ray diffraction is the preferred method of analysis for crystalline silica. Many sampling and analytical methods are prescribed by MSHA and OSHA (typically these are NIOSH methods, available at www.cdc.gov/niosh). A list of AIHA-accredited labs is available at: www.aihaaccreditedlabs.org/Pages/ListofAccreditedLab.aspx.

x. A job safety analysis is a process of systematically evaluating industrial processes or procedures, individual jobs, and individual tasks, and eliminating or reducing the risks or hazards to protect workers from injury or illness.

xi. The operator should direct the initial sampling towards those jobs or operations that have the highest potential for employee exposure. The purpose of this approach, known as a Targeted Sampling Strategy, is to quantify excess exposures if they exist. Subsequent targeted sampling should assess the effectiveness of installed controls. Targeted sampling should continue until all potentially high-exposure jobs have been assessed. Targeted sampling is also conducted following acquisitions, employee or community complaints, regulatory over-standard results, and for litigation or insurance purposes.

xii. This type of targeted sampling can be referred to as Case Closing sampling, but exposures must still be reevaluated any time there this a substantive change in the underlying processes or exposure controls.

xiii. Alternately, to ensure that the random sampling does not by chance omit certain entire employee classifications or work areas or shifts, the operator may prefer to use the "stratified random sampling" approach. Stratified sampling requires the collection of a predetermined number of random samples from each group of employees that have similar characteristics—for example, the same job classification, same work shift, or other similar attribute that may affect exposure patterns. To ensure that the entire workforce is adequately characterized the stratification of jobs needs to include all different job groupings at a site.

xiv. Because many health hazards are associated with chronic illnesses, data that span many years are critical to understanding possible exposure–response relationships. Therefore, exposure data are typically retained for at least 30 years following termination of the employee sampled. Exposure data that are representative of the jobs at a site have relevance to other employees who also worked that job but may not have been sampled. These types of data should be maintained indefinitely, and in compliance with regulatory requirements for record retention.

xv. Recommended tests include a chest x-ray meeting the specifications found in Public Health Service Specifications for Chest Roentgenograms (42CFR 37.41) or equivalent that is interpreted by a NIOSH-certified "B" reader (www.cdc.gov/niosh/topics/chestradiography/breader-info.html); a pulmonary function test; and an audiometric exam.

xvi. The MSHA Assistant Secretary stated in June, 2011, his intent to restart the program following its earlier suspension.

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Chapter 7
Extraction Principles

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7.1 Introduction

The term *extraction*, as used in this handbook, includes the planning and design for removal of rock, sand and gravel from the ground. The term extraction also includes the actual removal or mining process and the reclamation of the land after mining is complete. Each different method employed for extraction is unique and contains numerous interrelated components. A simplified description of the extraction process consists of the removal of rock, sand or gravel from its natural state and delivery of this material to the primary crushing or sizing facility in optimum physical dimensions for continued processing. The term extraction is often used interchangeably throughout this chapter with the terms *mining* and *quarrying*. Also the term *mine* is used interchangeably with the terms quarry, pit, underground quarry and underground mine.

Scope: This chapter examines the design, planning, development, operation and reclamation of an aggregates extraction operation, but does not provide the specific design information available from numerous manuals and texts. The primary function of this chapter is to describe the extraction system in terms of how its various components interrelate and how the system as a whole interacts with the remainder of the aggregates production operation. Overall environmental and community concerns associated with pit and quarry development are covered in Chapter 4, while processing principles of the rock after extraction are considered in this chapter.

Planning

Before any extraction system can be implemented, significant short- and long-range planning must be performed. This planning may range from a simple statement of "I think the quarry should be about here," to a complex, computer-aided analysis of numerous alternatives with the final result being a design optimizing all pertinent factors influencing the economics of the proposed project, including post-mining land use or reclamation. Computer-aided planning and design methods can aid in application of data collected for purposes of mine planning but do not replace the necessity for adequate exploration and an adequate analysis of geological data. It is essential to the programming of capital expenditures that all factors impacting the local environment be considered at the outset of the planning process. Once assembled, all data pertaining to geological conditions, environmental influences, anticipated production schedules and required plant must be analyzed to optimize investment schedules. This process, which can be completed by manual methods, is expedited with the aid of computerized planning and design methods.

When a pit or quarry design is complete and the necessary permits have been obtained, the operator begins the detailed equipment selection and procurement process, as specified in the *Long-* and *Short-Term Plans*. The *Long-Term Plan* covers approximately five or more years and contains significant input from the top levels of management. The *Short-Term Plan* normally addresses the specific decisions to be made within a one-year time frame. The plans, equipment selection and procurement process are heavily influenced by the decision of whether or not to employ contractors during development of the extraction system and/or production.

An important goal during development of the extraction system is to finish it as quickly and inexpensively as possible. The faster the mine is placed in production, the sooner the operator can begin offsetting capital expenditures with revenues, which is critical to efficient expenditure of capital. In this chapter, the term *operator* means the person or company who operates or owns the aggregates production facility. *Capital* is defined as the money spent to build the plant and purchase the equipment—not the money spent to operate the facility.

Updating Plans

Regardless of how comprehensive the original Long-Term Plan is, the production phase begins with a series of *adjustments* during which the newly constructed extraction system is comprehensively field tested to obtain maximum efficiency. These adjustments constitute the basis for making revisions to the Long- and Short-Term Plans. The extraction operation is very dynamic, continuing to grow and change throughout the life of the mining operation. The system is continuously observed, analyzed and modified. The original extraction plans are constantly updated to reflect the many changes affecting the system. Examples of these changes include:

- Localized irregularities in geology, such as unknown faults or water courses, seams of below-standard material or undulations in the deposit's topography;
- Unforeseen changes in market demand, such as product specifications, number of producers or customer requirements;
- Changes in regulations requiring different production methods; and
- Advancements in technology making available lower cost production methods.

Cost of Production

Probably the most common method for expressing an operation's level of efficiency is to determine the total cost of extraction per ton of material removed or simply *cost per ton*. Using this measure, the operator includes many factors which have varying levels of influence on the operating cost. In other words, any action the operator takes during the extraction process has an associated cost. Reducing one segment of the total cost might cause another segment to increase. But when considered collectively, the overall cost per ton represents the overall efficiency of the operation. For example, the blasting segment of overall cost per ton can be decreased by changing to a less expensive explosive. The lower cost explosive may not, however, fracture the rock as efficiently, thus necessitating additional expenditure later in the process to reduce the size of the rock. *Therefore, the net effect to the overall cost per ton must be examined to determine the efficiency of a change to the extraction process.*

To minimize cost per ton, which is normally the ultimate goal, the operator actually has an apparently conflicting goal: produce the maximum quantity of material while spending the least amount of money on non-production related areas. For example, the operator can produce a large quantity of material while spending a minimum amount on equipment and property maintenance. However, if maintenance is neglected or postponed, equipment will fail prematurely. When this happens, the operator experiences unnecessary expenditures either from lost production time or equipment repair. This type of expenditure can be minimized if the operator properly maintains the equipment and operating environment according to a predetermined schedule. If neglected, the seemingly unimportant aspect of equipment maintenance can easily become the basis for the most pronounced form of waste the operator encounters.

Reclamation Planning

Reclamation planning is normally completed before active development begins. In many cases, detailed reclamation plans must be complete before regulating agencies will issue mining permits. A small amount of reclamation, in the form of setting aside topsoil to be used during final reclamation, is done during the development phase. This sequence takes place throughout the life of the operation each time the operator removes more overburden to expose new areas for extraction. Although a portion of the reclamation occurs in conjunction with extraction in the form of property beautification, most reclamation occurs after extraction has been completed.

7.2 Planning

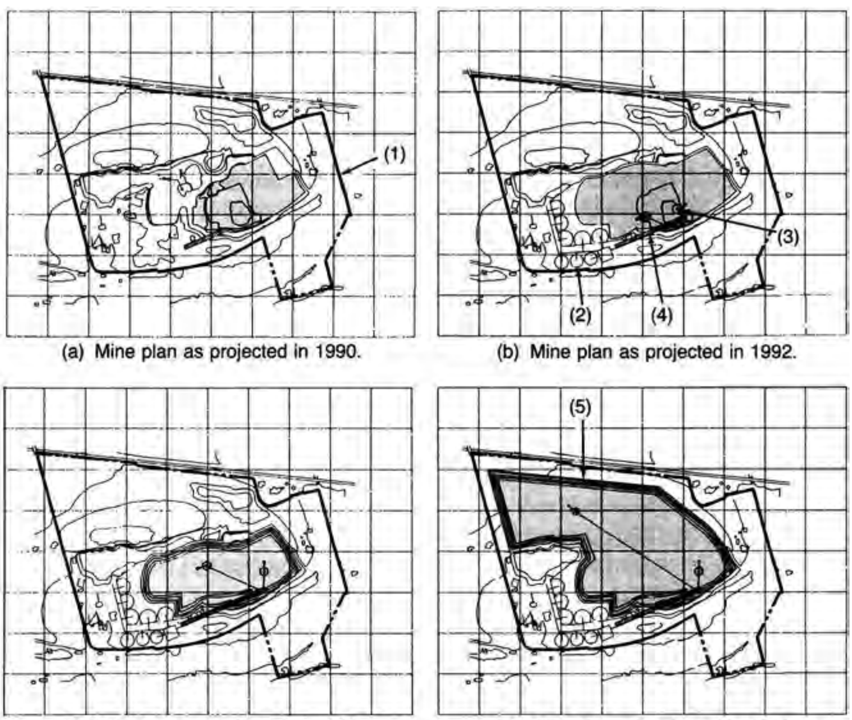
Pre-Production Design Engineering

Before any detailed design can be performed, the extraction engineer must collect a wide variety of information including all necessary data pertaining to the prevailing environmental, regulatory, health, safety and community concerns; all available information on state-of-the-art extraction equipment and technology; prevailing economic variables, including interest and inflation rates and general economic outlook for the local market; a working knowledge of basic aggregates properties such as hardness, soundness, abrasion and friability and how they relate to the products to be produced; and a thorough knowledge of the geologic model of the deposit created from the exploration program results. These important factors are addressed in Chapters 3 through 5 of this handbook. A description of the proposed plan for the processing plant also is necessary, as described in this chapter. The remainder of this chapter discusses how each of the above factors affect the extraction process.

Role of the Extraction Engineer: The aggregates industry is characterized by small staffs and low overhead, which tend to de-emphasize specialization. The result is the assignment of multiple job responsibilities to members of the professional staff. A staff engineer or superintendent might be called upon to analyze geological information. The same person also might participate in the design of the extraction process, the processing plant, the infrastructure system and the product loadout system. Finally, this person might conduct a financial analysis of the proposed project. Therefore, the term extraction engineer, as used in this chapter, refers to an individual experienced in the aggregates industry, with formal or informal training in any of a variety of disciplines including geological, mining, civil, mechanical, industrial or electrical engineering.

Perhaps the most important characteristic which the extraction engineer must possess is flexibility. The importance of flexibility cannot be stressed enough. The marketplace and the geology of the deposit, neither of which can be precisely anticipated or controlled, have more influence on the success of the operation than any other factor. Therefore, flexibility must be engineered into every phase of the operation so that unforeseen changes can be accommodated in the extraction process with a minimum of inconvenience and expense.

Optimizing Mine Designs to Site Geology: No two extraction systems are exactly alike, since the geology of each deposit is different and requires a unique design. One aggregates deposit, for example, may consist of granite extending for hundreds of miles in all directions while another might be composed of a 30-foot-thick bed of limestone. The extraction engineer must decide how to access and develop the deposit for production, whether surface or underground mining methods will be used, what types of equipment are necessary to accomplish the chosen extraction method, and how the mined-out deposit will be reclaimed in an environmentally sound manner. Therefore, all information affecting the ultimate extraction design must be obtained and utilized to develop the best overall plan.



(a) Mine plan as projected in 1990.

(b) Mine plan as projected in 1992.

(c) Mine plan as projected in 1998.

(d) Mine plan as projected in 2020.

Courtesy of Continental Placer, Inc.

(1) Property Boundary
(2) Plant moved down to second bench in quarry
(3) Portable In-Pit Primary Crusher
(4) Conveyor Access Ramp from Primary Crusher to Plant
(5) Ultimate Quarry Boundary

Figure 7.1 Examples of computer generated mine plans.

First, the extraction engineer compiles information regarding the geology of the deposit, the geographical, topographical, political and physical boundaries in which the system must operate, and the proposed locations of the processing plant and other permanent structures. Then, a preliminary design is prepared. The design is then compared with the preliminary designs of the other components in the operation, such as the processing plant, the office and scales, the equipment repair and maintenance shop, and the customer loadout facilities. The optimization of the extraction process then begins. This optimization consists of a series of compromises among the various individual segments of the operation in terms of their influence upon each other. In this way, the benefits are maximized and the drawbacks minimized of each component and consequently the operation as a whole.

Computer-Aided Mine Design: With a definitive understanding of all prevailing constraints, the extraction engineer can make use of computer-aided mine design and drafting software. Some examples of this type of software are: PCMINE by Gemcom, Vancouver, British Columbia; CPS/PC by Radian Corp., Austin, Texas; and AUTOCADD (CADD) by Autocadd, Bothell, Wash. Figure 7.1 gives a basic example of a computer-generated mine plan showing how the operation will appear in four different years. Computer-aided design methods provide maximum advantage of the *"what if"* design concept to consider different design alternatives. As more *"what if"* conditions are examined, the plan gradually converges toward an optimum extraction design. Use of any of the various computer-aided design and drafting (CADD) programs available eliminate the tedious and time-consuming manual iterative process. Multiple design iterations, which can be completed in minutes rather than days, are now possible using CADD software, available through consultants, minerals industry software companies and independent software writers.

Final Design: The final design, complete with all accompanying plans, provides the basis for three important steps. First, the package of information which accompanies the pit or quarry's operating permit application must, in most cases, contain detailed descriptions of the operation and accompanying reclamation plans. These descriptions are generated by the extraction engineer during the stage of *Pre¬Production Design*. Second, the Long-Term Plan is developed at this stage, based on the extraction system design. And third, the pre-production design provides the basis for the preliminary budgeting process.

Long-Term Planning

The pre-production design discussed in the preceding section conceptually describes the extraction operation from start to finish. To implement this concept, various sets of plans are needed, which make the logical transition from concept to reality. The first of these is the *Development Plan* which details the procedure for constructing and operating the extraction system. Thus, the *Development Plan* actually consists of two parts; the *Pre-Production Development Plan* and the *Ongoing Development Plan.*

The second type of plan is the *Long-Term Plan,* which, in contrast to the Development Plan, details how the extraction system will actually operate after development ends and production begins. The length of time covered by the Long-Term Plan varies with individual operations and operators, but normally covers periods of time varying from five to 20 years.

The life of most aggregates extraction systems is very long, usually in excess of 30 years. Many factors affecting the operation, such as technological advancements, regulatory changes and economic fluctuations, can and do dramatically impact the planning process. Therefore, the Long-Term Plan is updated periodically to reflect these changes. Although updating may take place as often as every year, it is generally performed every three to five years.

Comparison of Long- and Short-Term Plans: An important characteristic of Long-Term Planning is that it tends to be more philosophical in nature than Short-Term Planning. It incorporates, to a greater extent, the philosophy of the company's upper levels of management and thus provides a vehicle for their input. In contrast, the Short-Term Plan tends to be developed with more input from the lower levels of management. In theory this is an appropriate system, since top management should have a far-reaching vision of the entire company rather than a vision limited to just one pit or quarry. Lower level management, on the other hand, is more closely associated with local, day-to-day operations and the prevailing socio¬economic climate, a knowledge of which is very important for Short-Term Planning.

The key difference between Long- and Short-Term Planning is the level of detail. As an example, the Long-Term Plan might specify that small, low-capacity haul trucks will be replaced by larger models after five years to more cost-effectively accommodate the increased haul distances which result from the expansion of a pit or quarry. The Short-Term Plan details the exact procedure for purchasing the trucks based on more current information including: current equipment condition, prevailing economic factors and availability of acceptable, low-cost, used equipment. The Long-Term Plan is very broad in scope and usually describes only major events in the course of the pit or quarry's life, whereas the Short-Term Plan details each individual event which will occur during the short-term period.

Short-Term Planning

Although an individual operator may have a formal daily, weekly or monthly operating plan, Short-Term Planning as described here most commonly covers either one year or one operating season. The actual time period for which the Short-Term Plan is compiled coincides, in most cases, with the pit or quarry's fiscal year. The fiscal year is used because the information gathered to prepare or update the Short-Term Plan is also required for the preparation of the annual budget. And the information used to prepare the annual budget is used to prepare the Short-Term Plan.

The Short-Term Planning process begins by examining the projected future course of events as described in the Long-Term Plan. Based on the broad, general long-term scope, the extraction engineer plans the coming year's activities in conjunction with personnel responsible for other areas of the operation such as maintenance, processing and product transportation. The Short-Term Plan includes:

- Where and how much overburden stripping must be performed for a surface operation
- Required pre-production development for an underground mine and where the development is to be performed
- Required location for extraction within the pit or quarry to be consistent with the Long-Term Plan or to provide adequate blending in the case of a heterogeneous deposit
- Required equipment purchases and dispositions
- Required new access roads
- Plans for trial of new types of equipment and supplies
- Other required major purchases
- Changes in the operation, such as an increased mining rate due to increased market demand, which warrant updating the Long-Term Plan

When the Short-Term Plan is complete and approved by the appropriate levels of management, the extraction engineer begins the necessary steps to execute the plan. One important step which is often overlooked or neglected is the continuous monitoring of progress according to the plan. Without continuous monitoring, the actual course of events can deviate from the plan, and consequently fail to accomplish the goals established by the Long-Term Plan. When a deviation occurs, time and money are lost in re-orienting the direction of the operation. Therefore, strict adherence to the Short-Term Plan is extremely important. Obviously, incidents will occur to upset the plan, but a well-conceived plan has sufficient built-in flexibility to accommodate unforeseen occurrences.

Underground Mining an Upward Trend

The percentage of crushed stone from underground mining is increasing. Presently, 109 underground mines exist in 14 states: 26 in Kentucky; 13 in Missouri; nine in Tennessee; eight in Iowa and Illinois; seven in Pennsylvania; six in Georgia; five in Indiana; four in Kansas, Maryland, Texas and West Virginia; three in Nebraska and Virginia; and one each in Colorado, New York, Oklahoma, Oregon and Utah.[18]

Several reasons help to explain the increasing trend of underground stone production:

- Permits are difficult to obtain for new quarries.
- Underground mining maximizes reserves on a permitted property.
- Selective mining of rock is possible.

What used to be the *NIMBY* (Not in My Back Yard) philosophy of neighbors and city fathers alike has degenerated into the *BANANA* attitude (Build Absolutely Nothing Anywhere Near Anything). This problem is made even worse by the fact that rapidly growing major cities, which need aggregates for development, are spawning new communities that are even more resistant to quarry development than the farmers they are displacing. An underground mine, that has minimal impact on the surface, may be more acceptable and therefore easier to get zoned and permitted. Farming can continue on the surface above an underground operation. At deeper depths to the mine workings, the occupants of homes may scarcely be aware of mining activities beneath them.

The geometry of a quarry layout tends to leave permitted reserves unmined beneath berms, haul roads, plant and stockpile areas and in setbacks. Significant portions of these reserves may be economically mined from underground. Access can be obtained through tunnels driven straight in from the existing quarry benches. Reserves left in the floor of a deep pit may be mined via a ramp cut at a 10 to 15 percent grade from the lowest point of the quarry.

The quality of rock deposits is not uniform. Stone quality and thickness varies from pit to pit and frequently from one side of a pit to the other. Customers do not always want the stone that can be easily mined or that is most common at any particular operation. Under these conditions, selective mining, which is difficult to perform in quarries, is required. Rock can only be recovered by mining downwards, by removing rock from the upper ledges first. Sometimes high value stone lies beneath rock of marginal quality or rock that must be wasted. Underground mining provides the operator with the ability to mine selectively, bypassing the poorer material and going straight to the desired stone. The slightly higher costs of underground mining frequently can be offset by the increased selling price of the better quality rock. The economics of selective underground mining are influenced by the minimum applicable specifications for the material.

Selection of Economical Haulage Systems

The correct time to install a primary crusher underground and carry the stone out of the mine by conveyor is a difficult one. Determining this time is not as simple as comparing just the capital and operating costs of a truck and loader fleet and a crusher/conveyor system. Establishing the proper time to install the crusher underground is even more complicated if the underground mine and surface quarry are operated at the same using the same primary haulage system. Factors to be considered in the rock haulage system selection for an underground mine are:

- Existing haulage equipment
- Productivity requirements—the system must be able to handle the needed production from the mine or quarry
- Capital costs of the major components—trucks/loaders and usher/conveyors including installation costs
- Labor—frequently the major portion of the haulage system operating costs
- Other operating costs—including maintenance and "consumables," such as fuel, truck and loader tires, crusher linings and conveyor belting
- Ventilation system to dilute the exhaust from truck and loader engines
- Haul roads—include cost of excavation, maintenance and loss of reserves

Discounted Cash Flow Method

Begin the analysis after all the above data has been accumulated. To compare haulage systems, the costs of all the factors that will be affected must be considered. The only way to compare complex streams of capital and operating costs over a period of time is the discounted cash flow method.[19]

In the discounted cash flow (DCF) method, estimate the total positive and negative affected cash flows though the life of the project. Use a project life of at least 20 years in the analysis. Include items such as replacement costs of equipment (including its scrap value) and the annualized equipment operating costs. Other more specialized items also must be included such as,

- Requirement if the mobile haulage fleet in an underground mine is increased; Increased ventilation capacity
- Large haulage ramps for two-way traffic from a surface quarry may tie up excessive reserves shortening the life of the mine
- Mechanization or automation of an in-pit-crusher or an in-mine-crusher and conveyor system may allow for increased productivity at lower operating cost

After the streams of cash flow are estimated, they are *"devalued"* according to the time value of money. *Devalued* means the fact is taken into account that a dollar today is worth more than a dollar next year.

One of the difficult parts of the analysis is estimating the discount rate to be applied to the cash flows. The discount rate is the rate at which money is considered to vary over time. Typically for stone operations this will be somewhere between 10 and 18 percent. For example, a discount rate of 10 percent might apply to long-established operations with a firm idea of costs and hence a relatively low risk of errors in the estimated costs. A rate of 18 percent might be appropriate for speculative operations. For comparing alternatives, a discount rate of about 14 percent is probably suitable for many operations. Most spreadsheet software programs, such as Lotus 1-2-3® and Excel®, will perform discounted cash flow calculations at the press of a button. Hence the use of a spreadsheet program installed on a personal computer is ideally suited for performing a discounted cash flow analysis. After the cash flows and a discount rate are entered into the spreadsheet, the *net present value* is calculated of the cash flows. The *net present value* is the value of the future stream of cash flows in today's dollars. The alternative with the highest net present value is preferred.

7.3 Surface Mining

In the aggregates industry, a wide variety of methods is used to extract the raw material from its natural state. These methods are broadly categorized into those used in the production of (1) sand and gravel and (2) crushed stone. This categorization is due to the geological environment in which the two resources are found. Crushed stone is produced from solid rock formations and must normally be drilled and blasted prior to extraction. The area in which the drilling and blasting operations take place is referred to as a *quarry*. The broken rock generated from the blast is referred to as *muck* or *shot rock*.

Sand and gravel products are extracted from unconsolidated deposits which do not require drilling and blasting. These deposits occur at or immediately beneath ground level or on the bottoms of streams, lakes or oceans. When sand and gravel products are extracted from deposits at or near ground level, the mining area is called a *pit*. A quarry is also sometimes referred to as a pit. Other types of sand and gravel extraction areas are not given a name such as pit or quarry, but are referred to by the type of deposit, such as a stream deposit, lake deposit or marine deposit. Chapter 3 provides detailed information on these types of geologic deposits.

Quarry Development

Once the overall quarry design is complete, the development sequence is formulated to ensure the production of saleable products at the earliest possible time. This sequence normally includes stripping a sufficient amount of *overburden* to access the deposit and establish a working face from which the production sequence can begin. In the event the deposit outcrops or protrudes above the surrounding surface, the stripping of overburden for the most part is not required. However, the establishment of a *production face*, which is an area of exposed rock where production blasting can take place, remains the essential first element.

Commonly, all or part of pre-production development is performed by a contractor, for two basic reasons. First, specialized equipment, which the quarry operator usually does not own, including scrapers, backhoes, bulldozers and the personnel to operate them frequently are required for the stripping of overburden. The operator may not wish to acquire this expensive equipment for the relatively short duration of overburden removal since the equipment may not be required for the long-term mining operation. Additionally, financing costs and total costs are reduced the longer an operator delays the purchase of major equipment. These lower costs make the project easier to finance if delay in purchase of the major items does not impact on the long-range production capacity of the plant.

Stripping Methods: The method used for overburden stripping is determined by the type and thickness of material to be removed. Overburden ranges from loose soil to solid rock or combinations of the two. Soil and partially weathered rock can be removed by pushing it into piles using a bulldozer, and then removing it with conventional loaders and haul trucks. Harder or more consolidated material requires drilling and blasting. Very often the surface topography of the deposit is irregular, thus causing the removal of the overburden at the immediate contact with the deposit to be very costly and difficult. Whatever method is chosen, care is taken to separate the organic topsoil from the remainder of the overburden since use of the topsoil is required during the reclamation phase.

Stripping Sequence: The area to be initially stripped is usually minimized to keep the pre¬production development cost low and to begin production quickly. After production starts, stripping continues as a normal part of the production sequence. Many pit and quarry operators choose to perform the stripping requirements for the year over one short period of time with the accounting for the cost of stripping being spread out over the entire year (i.e., *annualized*). Stripping is scheduled at a convenient time to minimize interference with peak production periods. Careful planning is required when determining where to move the stripped material so it will not be stored where future mining is to take place, thus avoiding rehandling. Also, the effective placement of overburden provides a substantial sound barrier for the surrounding neighbors.

Haul Road Development: When pre-production stripping is complete, development continues with the excavation of the primary haul road down into the deposit or up onto the outcrop. The haul road provides access to the production face which is where the extraction sequence begins. The location of the primary access haul road is based on the following factors: orientation of the deposit in relation to the processing facility; optimum location in the deposit to begin production considering overburden thickness, quality of the material and other geologic factors; the bench or face height selected as optimum for production blasting; and the possibility of subsequently relocating the primary crusher in the quarry.

The haul road logically follows the shortest route from the processing plant to the point where production begins. At the same time, however, many other considerations enter into the haul road geometry decision. The haul road should be located so that it will not have to be moved later as the pit or quarry expands. Extraction normally begins where the material to be processed is of satisfactory quality and the amount of overburden to be stripped is minimal. The haul road must access that location in the most cost effective manner possible. If a primary crusher is to be located in the quarry at some time in the future, the haul road might be initially designed to act as the route for a conveyor leading from the in-pit crusher to the remainder of the processing plant. Or, the haul road might provide access to critical points in the conveyor system.

Grade: The primary access haul road normally begins very near the proposed location of the primary crusher and proceeds directly to the initial mining face to minimize haulage distance. The slope and width of the road are determined by the requirements for optimum, safe operation of the equipment which use the haul road. Most haulage equipment is designed to operate best on slopes of less than 15 percent. Of course, the flatter the haul road, the less strain the equipment experiences. On the other hand, the steeper the haul road, the shorter the access is to the desired extraction area. The trade-off in haul road grade normally occurs at a slope between 10 and 15 percent. The road's configuration, including the direction, number and radius of curves, and the location of the road within the overall quarry configuration is determined by the preference of the operator considering the proposed mining sequence for the deposit and the optimum geometry for the haulage equipment as specified by the manufacturer.

Width: The width of the haul road is determined when considering the haulage equipment dimensions and requirements governing haul road clearances, drainage and haul road berms. A haul road berm is a mound of dirt or rock placed along the edge of a road to delineate the edge and minimize the possibility of vehicles leaving the road in the event of loss of control. These and other haul road requirements are specified in the Mine Safety and Health Administration (MSHA) regulations for hauling equipment referenced in Chapter 6.

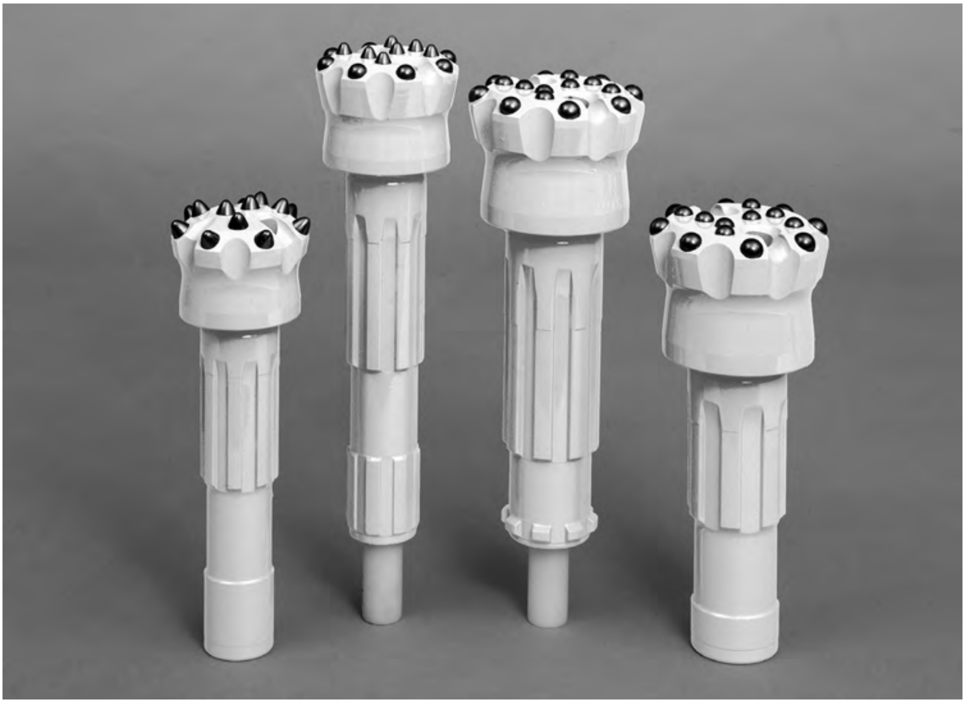
Computer Design: Modern computer-aided design, available from most major haulage equipment manufacturers, allows the selection of the optimum haul road location and geometry taking into account all possible variables, the most significant of which is often equipment capability. For example, given sufficient information, including the manufacturers' equipment performance specifications, an optimum combination of equipment and haul road geometry can be determined which is probably more cost effective than used in the past. These computations can be performed manually,[1] but the use of a computer and suitable software allows a very rapid examination of all possible combinations of significant variables. Important variables include forecasted changes in the cost of fuel, oil, grease and tires; expected disposition market when the equipment reaches the end of its useful life; and various inter-company equipment exchange scenarios. Manufacturers who have computer programs to analyze haulage requirements include the following: Caterpillar, Inc., Peoria, Ill.; Volvo-Michagan-Euclid (VME), Cleveland, Ohio; Terex Corp., Hudson, Ohio; Payhauler Corp., Batavia, Ill.; and Komatsu Dresser Co., Norcross, Ga.

Drilling and Blasting

A wide variety of drills and explosives is used in the surface quarrying industry because of the diversity of rock types and formations mined for aggregates.[1,2] Factors affecting the type of drill used include deposit geology and thickness; rock hardness and chemical composition; climatic conditions; and regulatory, geographical and local restrictions.

Type Drills: Rock hardness and composition determine the basic type of drill used. In softer-type rocks such as soft limestone, for example, a *rotary drill* using a drag bit usually is employed. This type of drill employs rotation and down-pressure to force the drill bit into the rock. On the other hand, if very hard rock is mined, a *down-the-hole* (DTH) or *in-the-hole* (ITH) *hammer drill* (Figure 7.3) normally is used. When the rock is highly abrasive, a drill bit containing tungsten carbide inserts is required. The DTH and ITH drills use pressure, rotation and a hammering action to penetrate the rock. In medium-hard formations, a rotary drill using a *tri-cone* bit may be the best alternative. As the rock hardness and abrasiveness increase, the drilling cost increases due to slower penetration rates and increased cost of the drilling equipment. The type of drill bit used typically varies dramatically as different areas within the same deposit are mined and the bit configuration and composition are optimized to match prevailing geological conditions. (See various drill bits in Figure 7.2.)

Drill Mounts: Most drills are mounted on either a rubber-tired truck capable of traveling at relatively high speeds or on bulldozer-type crawler tracks which can negotiate rough terrain and steep inclines. The type of drill carrier used is determined by the terrain and distance between drill patterns. The drill may either have its own self-contained power source or require auxiliary power. The drill mast usually varies in height from about 20 feet to 60 feet. Mast height is selected based on the proposed *production face height* (i.e., height of rock face to be blasted) and drill steel lengths available.



Atlas Copco

(a) DTH Bits, various types

(b) Secoroc DTH Bit

(c) Secoroc Epsilon Bit

Figure 7.2 Common quarry blast hole drill bits.

Atlas Copco

Figure 7.3 Down-the-hole hammer drill.

If the face height requires the drilling of 60-foot holes, the operator may use a drill with a mast height capable of accommodating two 30-foot drill rods (also referred to as *drill steel*) rather than one 60-foot drill rod. A drill with a 60-foot mast costs more than one with a 30-foot mast, and a 60-foot drill rod costs more than a 30-foot rod. When drilling 60-foot holes with a 30-foot drill, however, the driller must add a second drill rod half way down each hole and remove it upon completing the hole. The cost associated with the time lost to add and to remove a second drill rod must be considered when purchasing the less expensive drill having the shorter mast.

Drill Hole Size: The size of the holes drilled for blasting in surface quarries are typically three inches to seven inches in diameter. Many operators begin production using one size hole and, over a period of time, change to a different size hole as varying geologic conditions are encountered and different types of explosives are employed. Usually, larger diameter holes result in less total drilling and blasting costs. Lower overall costs can result from an increase in the size of drill hole with a resultant decrease in the number of holes required. The larger holes contain a greater quantity of blasting agent and cause fragmentation of a greater tonnage of rock. The most cost-effective choice of hole diameter and blasting agent is determined only by experimentation in the field. For this reason, drilling contractors are often employed in the early phases of development to allow experimentation with drill types and hole sizes before equipment is purchased.

Optimizing Blasting: Initial selection of a combination of drill and explosive may be most cost-effectively accomplished utilizing the expertise and computer programs available from drill and explosive manufacturers and suppliers. These programs estimate the overall cost of various alternatives at accuracy levels approximately proportionate to the reliability of the geological data available. The software used in this type of analysis is generally the property of the blasting or explosive company and is normally not for sale but can be obtained by hiring the company on a contract basis. The benefits derived from use of these programs are normally part of the total blasting service. Companies that have blasting computer programs include the following: Explosive Technology International, Inc., Atlanta, Ga.; Atlas Powder Co., Dallas, Texas; Austin Powder Co., Cleveland, Ohio; and IRECO, Inc., Atlanta, Ga.

Field Trials: In conducting field trials to select the best combination of hole size, hole spacing and explosive, all variables except the one being tested are held constant. The goal is to determine the least cost and amount of explosive to use while providing the desired level of rock fragmentation with a minimum amount of vibration. For example, the blast hole drill pattern can be held constant for several blasts using several different types of explosives. The overall cost, rock fragmentation results and vibration levels are monitored until the most efficient explosive is found for the existing condition. Alternately, the same explosive might be used, but the spacing of the drill pattern varied until the cost as a function of quantity of fragmentation is optimized. *An important concept to remember is that fragmentation of rock by primary blasting is more cost effective than fragmentation by mechanical crushing or secondary breaking.*

New types of explosives, drill bits, drills and other innovations should be evaluated as they become available. Many excellent references are available on drilling and blasting concepts.[2,3,4,5] The extraction engineer should consult these references and be familiar with the concepts used to calculate *burden* (the distance between rows of holes), *spacing* (the distance between holes in a row), explosive energy, hole diameter and the many other factors affecting rock fragmentation for specific deposits and production requirements.

Explosive Products: Although many types of explosive products are used for quarry blasting, the most widely used is a mixture of fuel oil (FO) and Ammonium Nitrate (AN), which is a common fertilizer. When combined in precise proportions ANFO is formed.[3,4] ANFO is a *blasting agent* and not an *explosive* because it is not easily detonated. Chemical mixtures used in blasting, which cannot be detonated by a blasting cap alone, are called *blasting agents*. A small quantity of high strength explosive must be used together with a blasting cap to detonate blasting agents, which adds an additional level of safety to quarry blasting. In contrast to blasting agents, chemical combinations which can be detonated by a blasting cap are referred to as *explosives*.

Loading and Hauling

Equipment Size: The aggregates industry includes plants which vary in productive capacity from as little as 100,000 tons per year to others with capacities in excess of 10 million tons per year. For this reason, there is not a single size of loading and hauling equipment which can be considered standard for the industry. The typical aggregates operation produces approximately 450,000 tons each year. This size operation normally utilizes off-highway trucks with capacities in the range of 35 tons to 85 tons. Smaller plants usually employ trucks with capacities in the 15- to 20-ton range while the largest plants might optimize their needs with truck capacities as large as 175 tons. Figure 7.4 shows a typical haul truck being loaded in a quarry.

Fortunately, manufacturers have standardized the sizes of equipment to a great extent. Standardization limits the number of choices available and keeps the prices of trucks and loaders lower for the capacity range used in most pits and quarries. Although the majority of operations use rubber-tired front end loaders in the 6- to 13-yard^3 capacity size (Figure 7.5), power shovels in the same general size range are sometimes used (Figure 7.6). Until recently, small diesel or electric-powered, cable-type shovels were the standard, but advancements in hydraulic technology have lead to major increases in the use of hydraulic power shovels in quarries.

Operating Cost: Generally the unit operating cost decreases as the size of the equipment increases.[6,7] However, if the capacity of large equipment is under-utilized, a smaller unit is usually more cost effective. The data presented in Table 7.1 shows that a 13-yard^3 loader costing $120/hour to own and operate, can load 1,400 tons per hour at a cost of $0.09/ton. A 7-yard^3 loader operating at $70/hour can load 700 tons/hour at a cost of $0.10/ton. However, if the 13-yard^3 loader, due to production restrictions elsewhere in the operation, works at a lower production rate, say 1,000 tons per hour, it still costs $120/hour but results in a cost of $0.12/ton. In a facility producing one million tons/year, use of the larger loader results in an excess cost of $20,000.

Figure 7.4 Off road haul truck

Figure 7.5 Front-end loader.

Haulage Equipment Selection: Pit and quarry haul road configuration is determined primarily by the capability, availability and economics of the equipment since the surface topography and orientation of an aggregates deposit are fixed. Assume, for example, that the hauling equipment has a nominal service life of 20,000 operating hours and the mine operates 2,000 hours/year. This equipment will then be used for 10 years. If the equipment is to be used in the same operation for its full 10-year life, it must be sized to accommodate the hauling requirements for that period of time. During this period, additional haul trucks will be required as the active production areas move farther from the processing plant. Therefore, before acquiring the initial haul units, plans must be developed in identifying how these units will fit with the future haulage fleet. Small equipment might comprise the initial fleet with larger equipment supplementing the fleet in later years. In this situation, haul roads and dump areas must be constructed in the early years to accommodate the larger equipment to be used in the future.

Figure 7.6 Hydraulic power shovel.

Table 7.1 Haul Truck and Loader Matching

Hourly Production	Loader	Hourly Owning and Operating Cost[(1)]	No. Loading Passes	Target	Hourly Owning and Operating Cost[(1)]	Loads per 50 min hour
1,400-1,600 tph	13.5-yd Class	$120	4	85-Ton Class	$80	17
1,200-1,400 tph	13.5-yd Class	$120	3	50-Ton Class	$65	21
700-800 tph	7.0-yd Class	$70	5	50-Ton Class	$65	15
	7.0-yd Class	$70	4	35-Ton Class	$50	19
600-700 tph	4.0-yd Class	$75	6	35-Ton Class	$50	18
500-600 tph	5.5-yd Class	$60	5	35-Ton Class	$50	15

Note: 1. Operating costs are based on the first 10,000 hours of usage. Includes parts, labor, fluids, tires, and $15/hour operator.

Courtesy of Caterpillar, Inc.

Relocation of Primary Crusher: Another decision which affects the haulage fleet selection is the possibility of relocating the primary crusher in the quarry when the haul distance becomes excessive. An alternative is to initially install a portable primary crusher, which periodically is moved to remain near the working face, possibly completely eliminating the need for haul trucks. This option is becoming more prevalent in the industry as manufacturers perfect the technology of portable primary crushers.

Optimum Cycle Time: The loading equipment is sized to provide the optimum cycle time in loading the selected size and number of haul trucks. Ideally, the loading units should be kept busy constantly loading trucks. The trucks in turn should be kept busy hauling with delays held to a minimum. Table 7.1 shows the costs per hour to operate loading and hauling equipment. Conversely, these figures also represent the costs per hour lost when the equipment is not operating. Under maximum demand conditions, more than a few seconds of delay at any point in the cycle indicates either excess equipment capacity or restrictions in the system slowing the continuous movement of trucks.

Restrictions in truck movement usually occur in three places. First, if the haul road is too steep or too narrow, contains too many sharp turns or is not maintained in a smooth condition, the trucks cannot travel at the speed required for efficient operation. Second, if the initial dump location or primary crusher does not have sufficient capacity to accommodate the quantity of material to be delivered by the haul trucks, the entire loading and hauling fleet experiences unnecessary idle time when each truck waits to dump. Third, the haulers experience idle time if the loading and hauling fleet is not properly matched or the loading fleet lacks the capacity to keep the haulage fleet moving. *Constant monitoring of the load and haul system is essential to minimize wasted capacity and operating cost.*

Supplemental Equipment Purchases: As a pit or quarry expands, the tendency is to acquire additional pieces of similar-sized equipment to *fill in the gaps* in the loading and/or hauling capabilities. This normally results in a fleet which is less than optimum in size due to excess capacity somewhere in the system. To avoid this problem, an analysis of various equipment matching scenarios should be conducted prior to purchasing new equipment. Fleet analysis of this type is important to achieve optimum equipment balance. The pit or quarry operator should take full advantage of fleet simulation analyses to both initially build the fleet and for subsequent equipment purchases. This service commonly is available from equipment manufacturers at little or no cost. More detailed analysis software is available as an integral part of many mine design software packages (refer to Section 7.2) used in designing a new operation and its accompanying loading and hauling fleet.

Excess Capacity: Excess loading and hauling capacity is not necessarily undesirable. The extraction engineer commonly designs a certain amount of excess capacity into all phases of the system to allow for unforeseen circumstances which can disrupt production. Also, flexibility in the system is a critical component since production requirements often fluctuate dramatically. In northern climates, typical aggregates demand cycle shows little or no aggregates sales in the winter months due to the lack of construction activity. During the summer, however, demand for aggregates is at its peak with up to half of the year's requirements sold during a three-month period. But ideally, as in southern climates, an aggregates production facility is sized to produce a year's total requirements at a steady rate throughout the entire operating season. If the production facility has sufficient capacity to produce the three-months' peak demand during the three months of peak sales, excess capacity exists at all other times during the year.

Excess capacity is not a desirable situation because money is wasted in operating costs for larger than required equipment. Therefore, the most efficient operation has only enough equipment capacity to meet the average annual production requirements and therefore, obtain maximum usage from all equipment during the entire operating season. To provide the unavailable capacity in the summer months, the demand must be projected in advance so the difference between the maximum demand and the available production capacity can be produced and stockpiled prior to that time. During initial fleet selection, this production demand is forecast for each year of the operation's life and equipment purchases are planned accordingly.

Other Factors Affecting Equipment Selection: The number and size of trucks required for the fleet depends not only on production requirements but also on the profile and geometry of the haulage road that will exist throughout the equipment's useful life. Two factors which have nothing to do with optimizing the haulage fleet strongly influence the decision process for truck selection. First, if the operator has several pieces of surplus equipment from other operations or access to used equipment at an attractive price, it might be used regardless of size and capability. This decision is made by comparing the lower initial capital cost against higher operating costs. The other factor influencing the equipment selection process is familiarity with a certain type or size of equipment. If in the past certain types of equipment have demonstrated reliable, cost effective operation they may be selected rather than a new type or size of equipment even though the new, less familiar equipment might appear to be more cost effective.

For example, an analysis of the operation's requirements indicates an optimum fleet of three 50-ton trucks with one 7-yard^3 loader. The operator, on the other hand, has two surplus 35-ton trucks which are available for the new operation. One option is to purchase two new 35-ton trucks and the 7-yard^3 loader which, together with the existing two 35-ton trucks, provide adequate loading and hauling capacity. Using this alternative, the level of capital expenditure is kept lower. The fleet, however, would consist of four trucks rather than three, with a loader slightly larger than required. The use of this fleet would probably result in higher operating costs (Table 7.1) as compared to the other alternative of purchasing all new equipment. A complete economic analysis must be performed considering both initial and ongoing costs between the two options and a decision made based on the results.

Loading Equipment Selection: The selection of size, number and types of loaders is similar to that for selecting trucks, except that the loading equipment is matched to the predetermined hauling fleet. For example, if the production requirements indicate four 85-ton trucks must each make a complete cycle (from the loader to the primary crusher and back) every 15 minutes, the loader must be able to load a truck every 3.75 minutes. Theoretically, one 13-yard^3 rubber-tired loader has the required capacity, assuming no time delays (Table 7.1). In reality, delays and fluctuations in demand do occur, which would cause the trucks to back up at the loader, thus requiring an additional loader to keep the haulage fleet moving. The additional loader would likely be the same size (or smaller) depending on the operation's particular situation and loading requirements in other areas such as customer truck or rail car loading. Another alternative might be one 13-yard^3 power shovel which can load the trucks faster than the loader but is restricted in mobility compared to the loader.

Another factor entering into the decision between the use of a loader compared to a power shovel is the *digability* of the material. For example, some rock, such as granite and basalt, when blasted naturally forms a muck pile, which is extremely difficult to dig due to the interlocking characteristics of the shot rock. In this case a power shovel may perform better than a front-end loader due to its greater break-out force. *Break-out* force is determined by the machine's weight and resistance to movement when forcing its dipper or bucket into a muck pile. A power shovel can force its dipper into a tightly interlocked muck pile without pushing itself backward or spinning its tracks. Rubber-tired front-end loaders, on the other hand, often have difficulty avoiding tire slippage in this situation. If the shot rock forms very sharp, abrasive edges which easily cut rubber tires, chains can be installed on the tires of the loader (Figure 7.7) or a power shovel which has tracks instead of tires can be used.

In pits and quarries requiring simultaneous production from several areas, loaders are often preferred due to their speed and maneuverability. Equipment manufacturers usually cannot provide an unbiased comparison between loaders and power shovels since they normally do not supply both types of equipment in the same capacity range. Therefore, other companies who use the equipment being considered may be the best source for obtaining an indication of performance characteristics. The extraction engineer must remember that an equipment purchase decision results in very large capital expenditures and should be made only after objectively examining every alternative and source of information.

Figure 7.7 Tire chains for front-end loaders.

Secondary Breaking: *Secondary breaking* is the breaking of rock in the quarry following primary blasting. Secondary breakage is required when portions of the shot rock produced from primary production blasting are too large for loading, hauling or processing. These pieces of rock, commonly referred to as *over-size, set-backs* or *drop ball rock*, are undesirable when additional cost must be incurred to reduce them to a manageable size. The one exception to this is when the operator has a market for large-sized rip rap or jetty stone and therefore desires the production of very large pieces of rock.

Over-size material generally is caused by one of the following three reasons: (1) the drill hole pattern used for primary production blasting is improperly designed or drilled leaving too much space between holes or rows; (2) the blasting agent does not perform as expected due to the use of the wrong type or strength of blasting agent or the improper use of the correct blasting agent; or (3) the geology of the deposit prohibits optimum fragmentation. Poor fragmentation, for example, is likely in fractured granite deposits where much of the energy created by the expansion of gas from the blasting agent's chemical reaction is dissipated through existing fractures rather than in displacing the solid rock.

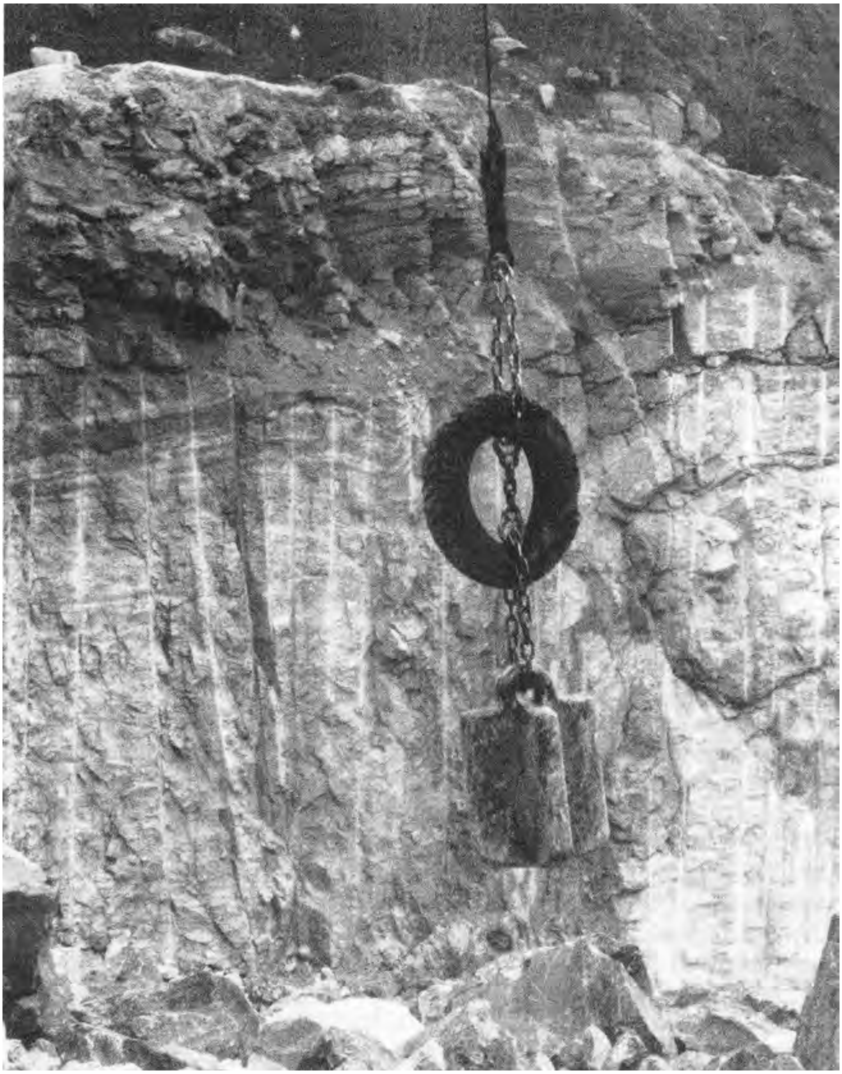
Equipment Selection: Numerous methods are employed for secondary breaking and depend primarily on the characteristics of the rock and the quantity of over-sized material to be broken. In the hardest rock deposits such as granites and basalts, secondary breaking is limited to the use of *secondary blasting* and *impact breakage*. In *secondary blasting*, small holes one to two inches in diameter are drilled in the over-sized rock, usually with a pneumatic percussion drill and charged with small quantities of high strength explosives. The desired result from secondary blasting is the reduction of the rock to a manageable size for loading and hauling with a minimum amount of drilling and blasting. Due to its extremely high cost, secondary blasting is normally employed as a last resort or where only a small amount of secondary breaking is required.

Secondary breaking by the impact from dropping a heavy weight on the rock is a more commonly used method in very hard deposits. A *drop ball* or *drop cross* (Figure 7.8) is used which is similar in concept to a wrecking ball employed in building demolition. The weight is repeatedly lifted using a crawler-mounted crane and dropped on the rock to be broken. This crane is referred to as the drop ball machine and normally experiences extremely severe use and accompanying wear resulting in greater than normal maintenance. The skill of the operator and the characteristics of the rock, including strength, hardness and structure, determine the required weight of the drop ball or drop cross, the height to which it must be lifted, and the number of times it must be dropped to obtain the desired breakage. In most situations, the drop ball or drop cross ranges in weight from five to 10 tons, is dropped 30 to 40 feet, and requires one to five repetitions to break the rock.

Secondary breakage is accomplished on weaker rocks using one of the following techniques: a drop ball, secondary blasting if the quantity involved is too small to justify the purchase of specialized equipment, a hydraulic impact hammer mounted on a large backhoe (Figure 7.9) or front-end loader or a concentrated impact device (Figure 7.10). The concentrated impact device places a large amount of energy in a very small area by dropping a confined weight a short distance onto a small-diameter point pressed against the rock.

Sand and Gravel Extraction

In contrast to the solid deposits of rock which are sources of raw material for the crushed stone industry, sand and gravel deposits are in a loose state. These loose deposits are mined without the necessity of drilling and blasting. Many of the types of equipment used in quarrying, such as front-end loaders, power shovels and haul trucks, also are employed in extracting sand and gravel from either dry deposits or those which can be dewatered.[8,9] In dry deposits the extraction process is very similar to quarrying, except drilling and blasting are not necessary. When the sand and gravel deposit is consolidated to the point where digging with a front end loader or power shovel is too difficult, a bulldozer equipped with a ripper is used to loosen the material. A ripper consists of a large tooth (or series of teeth) which is attached to the rear of the bulldozer and pulled through the material as the bulldozer moves forward.



Courtesy of Columbia Steel Casting Co., Inc.

Figure 7.8 Drop cross (drop ball).

Wet sand and gravel deposits include those which occur beneath bodies of water such as rivers, estuaries, lakes and oceans. Since these deposits cannot be dewatered, materials must be removed with specialized equipment such as dredges, draglines and floating cranes. Dredging equipment typically is mounted on floating platforms which allows them to move freely above the underwater deposits. Removal of the sand and gravel is accomplished either with large suction pumps which pull the material to the platform level or by one or more bucket excavators which carry the material up to the same level. At locations where dredging is performed near shorelines, it is not uncommon to utilize pumps and pipelines to transport material to on-shore storage locations.

Figure 7.9 Backhoe-mounted hydraulic impact hammer.

A floating crane uses a grab-type bucket suspended on a cable from a boom to raise the sand and gravel from the deposit. A dragline is a land-based crane which casts its bucket into the water above the area to be mined. The bucket is allowed to sink to the bottom and is then dragged back to the crane. As the bucket is dragged along the deposit, it becomes filled with material. The bucket is then raised out of the water, swung over the land and dumped.

Atlas Copco

Figure 7.10 Concentrated impact device.

Vulcan Materials Company

Figure 7.11 Example of quarry reclamation.

Reclamation

Regulations, community needs and environmental technology change very quickly. As a result, the final reclamation plan may require significant changes from the time of its conception to its implementation. After extraction is complete, the topsoil is usually replaced in the disturbed areas of the operation surrounding the pit or quarry to help in restoring vegetation, making these areas conducive to the development of parks, golf courses, shopping centers, housing developments and other uses. After the aggregates operation is abandoned, the pit or quarry can be allowed to fill with rain water and natural ground water, thereby creating a lake. Through creative reclamation efforts, the surrounding community is provided with a pleasant and useful recreation area using the pit or quarry lake as the focal point, as illustrated in Figure 7.11.

Sanitary Landfills: The conversion of mined-out pits and quarries to sanitary waste disposal sites is gaining importance. Some pits and quarries have several characteristics which often make them well-suited for this purpose. Aggregates operations usually are located near heavily populated areas having rapidly diminishing sanitary landfill capacity. They also have well established access from population centers where sanitary waste is being produced. Where the water table level is above the bottom of the pit or quarry, elaborate pumping systems are already in place which help to minimize the possibility of ground water contamination from the landfill. Once the pit or quarry is filled with sanitary waste and covered with topsoil, it is ideally suited for recreational use or shallow-rooted agriculture.

The potentially dangerous gases produced from the decomposition of trash in a sanitary landfill must be efficiently collected. These gases, when channeled into a collection system, can be used as an energy source. In geographical areas with small amounts of rainfall, long-term settlement of the landfill may be low. More extreme amounts of settlement, however, may occur where normal to high rainfall is experienced. Generally, permanent-type buildings construction on the landfill is difficult and costly due to expensive geotechnical engineering requirements.

Many pits and quarries can begin use as a sanitary landfill while aggregates extraction operations are still in progress. This dual utilization of quarries helps to simultaneously keep the taxpayers' cost of construction aggregates and waste disposal low. Existing environmental regulations and potential legal liabilities, however, pose significant roadblocks to use the mined-out pits and quarries as sanitary landfills.

7.4 Underground Mining

Development

Selection of Underground Mining: Underground mining normally is more expensive than surface mining and therefore, is not as common. Restricted access accounts for most of the increased costs associated with underground mining. As the value of the deposit becomes greater or as the ratio of depth of overburden to thickness of the deposit becomes greater, underground mining becomes more economically feasible. Assume, for example, that the cost to drill, blast, load and haul rock to the primary crusher by surface mining methods is $2.00/ton, excluding stripping. For the same total production, the cost of underground mining is $2.50/ton. Also assume the deposit is overlain by 100 feet of unsaleable material. Stripping and disposing of this material adds as much as $1.00/ton to the cost of stone from the first lift of open pit mining, thus raising the cost for that first phase of production to $3.00/ton. This makes the initial production cost of surface mined material $0.50/ton more than the cost of underground mining. However, this cost comparison must be continued before a long range analysis can be made. The underground mine will never have a stripping cost and the surface mine will have it only once. Subsequent levels of rock in the open pit quarry will not require stripping and will enjoy the $0.50/ton cost advantage. If the quarry ultimately develops several lifts, the tonnage of material produced at the lower cost will represent a savings that greatly outweighs the cost of stripping for the initial lift.

Relatively few operators are faced with a difficult decision between using surface and underground methods. To be suitable for underground mining, the material overlaying the deposit must have the ability to support its own weight when undercut by development openings. If the overburden is sufficiently competent to sustain undercutting, it is probably too thick and/or too hard to allow economical stripping for quarrying methods. Exceptions do exist, but in general the choice between underground and surface quarrying is relatively obvious.

Basic Considerations: Many unique factors exist when considering development of an underground quarry. The most important is probably the stability of the ground overlaying the deposit to be mined. Rock mechanics studies must be conducted to determine both the type of development sequence and mining method to use.[5,10] From examination of the geologic structure and determination of the rock's strength, rock mechanics studies are used as an aid in evaluating whether the ground is sufficiently competent to remain open without artificial ground support.

Support Methods: Various ground support methods are available, including *natural ground support,* which includes methods of excavation which use the inherent structural characteristics of the material excavated, such as shape of excavation and natural fracture planes. *Artificial ground support* includes any type of mechanical method or device which stabilizes the material surrounding the excavation. Artificial ground support includes the use of the following techniques: *rockbolts*, which are steel rods inserted and secured in holes drilled into the rock; *steel mesh* and *straps*, used in conjunction with rockbolts to secure the material between the rockbolts; *steel* or *timber sets*, which are a framework installed and secured inside the excavation in rock; *shotcrete*, which is a cement grout mixture sprayed on the rock surrounding the excavation to minimize subsequent deterioration from the natural environmental elements; and *pressure grouting,* which is the injection of a grout mixture under high pressure into holes drilled in the rock surrounding the excavation to fill fractures and minimize ground water inflows.

Ventilation: Adequate ventilation must be supplied to all underground workings.[11] Large fans force air through the mine to remove any hazardous gases present. In addition to the primary access tunnel, ramp or shaft, one or more additional openings to the surface are required for both completing the ventilation circuit and providing a secondary means of escape in the event of an emergency. Regulations limit the amount of diesel particulate matter (DPM) in the atmosphere of underground metal/nonmetal mines, including stone mines. There are three primary ways to reduce the DPM levels: newer, cleaner-burning engines, increased ventilation flows at the working places and reductions in the numbers and sizes of diesel units in use in the mines. Unless underground stone mines have adequate ventilation both coming into the mine (the main ventilation system) and at the faces themselves, then overexposures can occur.

Underground Water: Usually the removal of underground water by pumping is a major development and operational concern.[12] An efficient power distribution system and telephone communication network also should be established.[13,14,15] Each of these factors requires detailed engineering design prior to beginning underground mine development if work is to proceed in an efficient and cost effective manner.

Access: Once the decision is made to use underground mining methods, the means must be determined for access to the deposit. In the majority of underground quarries, the bedding of the deposit is nearly horizontal or lies at a shallow dip angle. If the deposit is exposed at the surface, a tunnel excavated horizontally into the deposit provides access. If the deposit lies at some depth below the surface, access can be achieved by sinking a shaft to the deposit, requiring mechanical hoisting of all material extracted. Use of a ramp excavated from the surface to the deposit is another possibility. If a ramp is used, off-road haul trucks or conveyors can be employed to haul the material to the surface.

Shaft access normally requires extremely high development expenditures per ton of production capacity and therefore is very seldom used in quarries. Shaft access can, however, become more cost effective than ramp access if the capital and operating costs for the shaft alternative are lower than for ramp access. When the rock to be extracted is at great depth, the development and production costs generally exceed the value of the stone regardless of the access method.

Ramp and tunnel access are the predominant methods used for access with the location of the deposit relative to the surface determining which method is most suitable. When a ramp is required to access the deposit, the angle at which it is excavated is one of the first planning decisions made. Usually underground ramps are steeper than surface ramps. The reason for this is illustrated by the following example.

Illustrative Example: Assume the floor of the deposit to be mined lies 400 feet below the surface. If the access ramp, which usually becomes the ramp on which the rock is hauled from the mine, is excavated at a 10 percent slope, the ramp is 4,000 feet long. At a development cost of $500/foot, the ramp costs $2,000,000 to complete. Amortized over a 15-year period at a production rate of 500,000 tons/year, the equivalent cost to develop the ramp is $0.27/ton. If the ramp is excavated at a slope of 15 percent, it is 3,000 feet long at a cost of $1,500,000 with an amortized cost of $0.20/ton. Therefore, by excavating the ramp 5 percent steeper, the operator saves $0.07/ton over the 15-year period on the cost of ramp construction. This savings, however, must be weighed against the additional cost incurred from hauling up a 5 percent steeper slope. For this example, the flatter ramp requires approximately three months longer to construct, which could be significant in the financial analysis where rapid return on investment is required.

In some underground mines, the access ramp is excavated as steep as 35 percent. The primary crusher is then installed underground and a conveyor is used to haul the crushed material to the surface. This type of system eliminates the extremely expensive long-distance, up-grade truck haul.

Access Location and Size: To minimize the required amount of ground support, the location and orientation of the access ramp are selected using the results from rock mechanics studies considering all geologic information. In unfavorable conditions, ground support can comprise a major portion of the development cost. An area having the least rock fractures, joints, faults and geological discontinuities is normally chosen for the access ramp. The cross-sectional dimensions of the access ramp opening are determined either by the maximum dimensions of the largest equipment which must pass through the ramp or by the size opening required for the passage of the required quantity of air for ventilation.

Some types of loaders and haul trucks are manufactured in a low-profile configuration for use where height is restricted. Many underground quarry operators, however, select common surface mine loading and hauling equipment which have the following important advantages:

- Standardization of parts inventory with other company surface operations
- Greater availability of parts and experienced mechanics
- Greater availability of used equipment
- Higher production capacity per dollar of capital expenditure since standard equipment has lower capital cost

To accommodate this high-profile surface mining equipment, under-ground quarries often are developed with relatively large openings.

Room and Pillar Mining: Some form of *room and pillar mining* is employed for all or part of most underground quarries. The basic sequence in room and pillar mining consists of excavating several wide, straight, parallel openings with regularly spaced, perpendicular interconnections. The unmined areas between openings form vertical columns of rock called pillars which are left in place to provide permanent support for the overlying material. The required minimum pillar dimensions and openings are determined using rock mechanics principles.[10]

A single lift quarry operation consists of mining at one elevation. In a multiple-lift quarry, which is performed in thick deposits, the top bench usually is excavated for a short distance, as illustrated in Figure 7.12. Then subsequent benches are started at lower levels and the sequence continues in this fashion. Each of the upper benches is kept far enough ahead of the lower benches to provide adequate working space on each lift. The rock excavated to form the openings between pillars becomes the quarry's production. The dimensions and spacing of the pillars are determined by the amount of support required for the overlying material and the strength of the rock which composes the pillars. The size of pillars vary as required but are normally about eight ft in length and width and spaced at intervals of 25 to 35 feet from center to center in a checkerboard pattern.[16] Other dimensions might be required to satisfy particular geological conditions. This method of mining requires that from 20 to 50 percent of the rock be left in place.

Drilling and Blasting

The type of extraction method used in underground quarries determines the method of drilling and blasting as well as the required type of equipment. In the majority of underground quarries, a conventional room and pillar approach is employed as described in the previous section. If the deposit is thin (up to 25 feet), it is normally drilled horizontally from the floor using a standard *drill jumbo* (Figure 7.13). In a thin deposit, extraction is accomplished in one pass, which is referred to as a *lift*. If the deposit is thick (greater than 25 feet), the initial pass is drilled with a jumbo, and surface mining-type bench drilling is used to extract subsequent layers as illustrated in Figure 7.14.

The procedure for choosing drilling equipment and blasting agents is similar to that described for surface quarrying. When very thick seams are mined in underground quarries, surface drilling equipment can be used with minor modifications to accommodate restricted opening sizes. The amount of *overbreak*, which is the fracturing of rock beyond the desired area, must be minimized in underground quarries since fracturing decreases the ability of the pillars to support the overlying material.

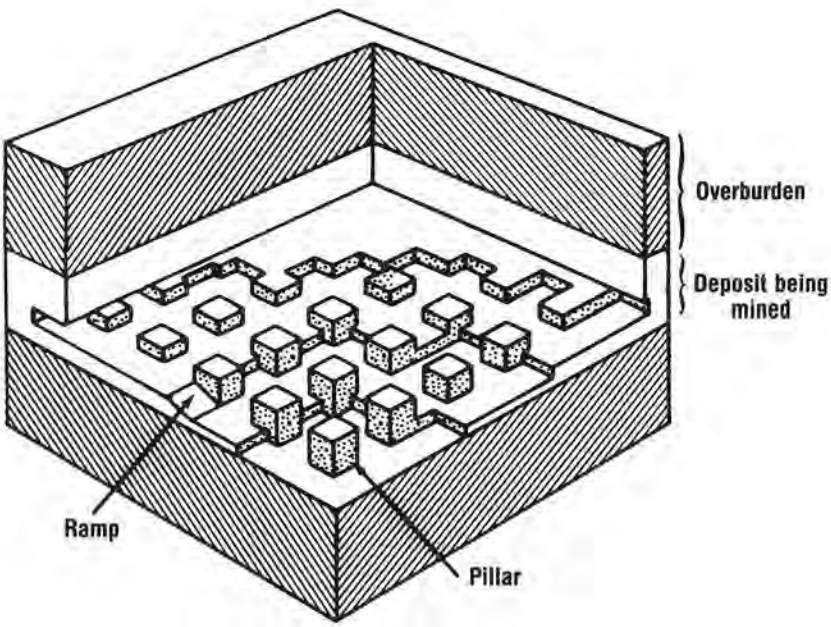


Figure 7.12 Room and pillar mining sequence.

Figure 7.13 Drill jumbo.

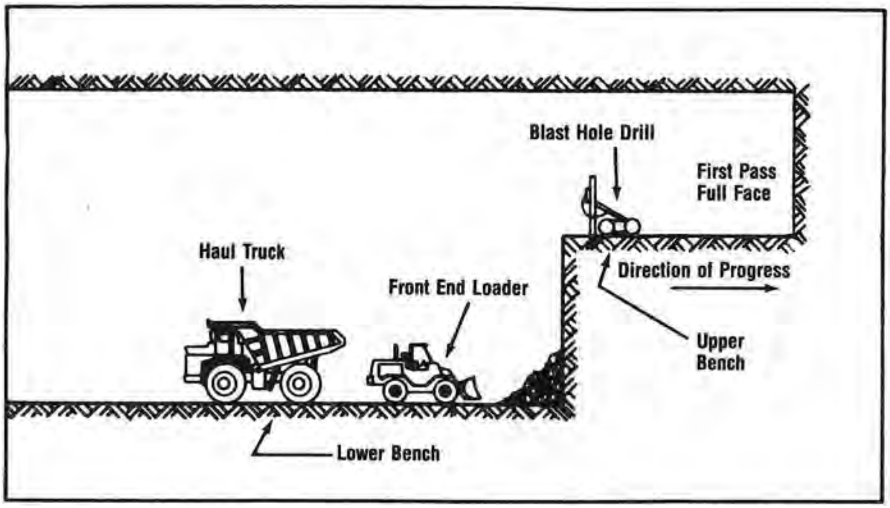


Figure 7.14 Underground bench mining section.

Drilling and blasting costs are relatively high in underground mines since the volume excavated in each blast is small. In contrast to surface quarrying, many small blasts are required rather than a few large ones. Also, tunnel-type blasting patterns are used for much of the blasting. Tunnel-type blast patterns are composed of short, small-diameter horizontal holes spaced close together. The quantity of blasting agent required to fracture a given quantity of rock, known as the *powder factor*, is often as high as two to three pounds of blasting agent per ton of rock blasted in underground quarrying compared to about one-half pound/ton in surface blasting.

Before blasting in underground quarries, the entire underground workforce must be evacuated from the mine. After the blast, workers must commonly wait 30 minutes before re-entering the mine to assure ventilation of hazardous gases and fumes. Underground blasting, therefore, normally causes excessive delays in production resulting in higher overall costs when compared to surface mining.

Loading and Hauling

Space is always limited in underground quarries, resulting in increased time to load trucks. Because of the high underground development costs, haulage ramps are often excavated wide enough for only one truck. The result is increased waiting time for trucks to pass at designated areas. When all cycle time delays are considered in fleet selection for underground mining, the result when compared to surface mining is often an increase in the number of loaders and trucks required. Analyses used to select an optimum loading and hauling fleet are described in Section 7.3.

The ventilation system in underground quarries must have sufficient capacity to remove the hazardous gases generated by the equipment's engines. Regulations allow most diesel engines to be used in underground quarries. Gasoline engines are not permitted due to their inefficient combustion and resulting noxious fumes. Many space restrictions and ventilation problems are eliminated by using a conveyor system to haul the material to the surface. In conjunction with the conveyor system, the primary crusher, which is discussed in Chapter 8, is installed underground to appropriately size the material for conveyor haulage. Although the initial capital cost of the underground crusher-conveyor alternative is usually higher than the truck haulage option, the operating cost of the conveyor is much lower. A detailed financial analysis must be conducted to determine the best approach for the specific conditions.

Post-Mining Uses

The following unique characteristics of an underground quarry present special opportunities for uses after quarrying has been completed or when mined-out areas become available:

- A fairly constant temperature throughout the year
- Location near or under a heavily populated area where land prices are at a premium
- Little flow of ground water into the quarry if deposit in which the quarry is located has few a joints, seams and other geologic discontinuities

Mined-out underground quarries are used for special purposes such as climate-controlled offices, warehouses and libraries. They also serve as parking garages and transportation networks and have been used for disposal of waste and for growing mushrooms. The utilization of mined-out underground quarries in populated areas eliminates the need to construct additional buildings or consume precious inner-city land and natural resources. Local, state and federal regulations must be carefully reviewed before selecting a post-mine use for a mined-out underground quarry.

7.5 Maintenance

Equipment Maintenance

Equipment in a pit or quarry environment experiences severe operating conditions due to the water, dust, rock and climatic conditions present. The length of time between equipment repairs is related to the frequency and level of maintenance performed. The required minimum amount of maintenance each piece of equipment should receive under normal working conditions is specified by the equipment manufacturer. No two pit or quarry operating situations are the same; consequently, each operator's maintenance program must be adapted to the individual conditions.

Philosophies: Philosophies regarding the required amount of maintenance vary as dramatically as the personalities of the operators. In some cases, the operator owns a spare piece of equipment for every one or two pieces in service to be used when a break-down occurs. This approach requires little or no preventative maintenance, but does require extensive repair capability and capital investment. At the other extreme, a comprehensive preventative maintenance program eliminates or minimizes the need for spare equipment. An equipment maintenance program can be managed through the use of computer programs available from most major equipment manufacturers, such as those given in Section 7.3 for equipment selection.

Optimum Approach: Selection of the optimum approach to preventative equipment maintenance includes the following factors: (1) the ownership cost of each piece of spare equipment; (2) the operating cost applicable to various levels of maintenance and/or repair capabilities; (3) facilities available for the repair of equipment for which a spare does not exist; (4) the cost of lost production while waiting for repair; (5) the expected duration between unplanned repairs given various levels of maintenance; and (6) the amount of time available in the production cycle for maintenance.

The analysis of comparing equipment requirements with the level of preventative maintenance begins by assuming no spare equipment is available. Then the costs of various levels of preventative maintenance are compared against required quantities of spare equipment. This comparison continues until the theoretical optimum balance is reached between capital outlay for spare equipment and maintenance cost. Usually the most cost effective program consists of no actual spare equipment, but rather some fraction of each piece of equipment designated as spare. This no-spare equipment fleet is coupled with an elaborate maintenance program managed by a computer-based scheduling and reporting system.

As an example, an analysis might indicate 3½ trucks are required to haul the necessary production. Probably four trucks will be purchased, thus leaving one-half truck as spare. Since only one-half of a truck's time is available for spare use, a maintenance program assuring minimum out-of-service time is required. Since the overall goal is to minimize cost while maintaining required production, a reduced number of high-cost pieces of equipment is usually chosen with a more intensive low-cost maintenance program.

Whether a maintenance program is computer-based or manually monitored, the system should, for each piece of equipment, have the following capabilities:

- Track all associated costs
- Record all operating time and repair or down time and the reason
- Analyze maintenance data and generate meaningful reports on scheduled maintenance, daily and period operating costs and historic trends

A maintenance system with this capability allows low-cost preventative action to be taken in advance of high-cost catastrophic failure. Also, the pieces of equipment can be readily identified which cost more than normal to operate together with reasons for the excessive costs. Comparisons can be made between the effectiveness of various types of components, motor oils and lubricants. And finally the use of a maintenance management system makes possible the identification of the optimum time for equipment replacement.

Mine and Property Maintenance

Pit or quarry maintenance, similar to equipment maintenance, is an important aspect of any operation and can reduce costs, increase productivity, reduce lost time due to accidents and increase employee morale. Haul roads probably require more maintenance than any area in the operation. When road maintenance is neglected, haul costs rise and productivity drops. Grading haul roads with a motor grader increases tire life on all equipment, eliminates bumps and ruts particularly where trucks must make sharp turns, and allows haul trucks to operate at the designed speed and the lowest cost. Spraying the road several times a day with water helps maintain a smooth hard surface and decrease dust.

Other areas in the pit or quarry requiring maintenance include safety and communication devices and installations, electrical distribution systems, and pumping and mine drainage systems. In underground quarries, ventilation systems must be constantly monitored, and loose rock on the walls and ceiling must be periodically removed. Loose rock on the walls of surface mines must also be monitored and removed as necessary.

Pit and quarry maintenance principles extend to all areas of the property. When an operation is clean, orderly and organized, employees, customers and the public all have a better perception of the operation and the operator. This is vitally important to the long-term success of the business. Employees are more likely to project a favorable image of their employer to neighbors when the workplace is safe and well maintained. Finally, the public is more inclined to accept the aggregates operation as a part of the community when the property boundaries and entrance are maintained in a clean, attractive manner.

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Chapter 8
Processing Plant Principles

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8.1 Introduction

The purpose of this chapter is to provide guidelines on the various integral elements in the development of an aggregates production facility. This chapter is intended for use as a reference source and not as a design manual. Aggregates plants are as varied as the materials handled and the products produced. Plant design is a function of experience and the response to continuing changes in technology. Accepted design guidelines as well as rules-of-thumb based on experience are given in this chapter.

The six major categories normally considered in the design and operation of a production facility to process a given natural mineral source into saleable, economic construction aggregates are:

- Processing parameters
- Project development
- Quality control
- Processing elements
- Plant design
- Automation

Processing plant principles are presented in this chapter for natural aggregates such as crushed stone, sand and gravel, although many of these principles also apply to other aggregates such as slag, light weight aggregates, etc.

A financial evaluation of a project is not covered since each situation is unique, and methods of calculation and criteria used for comparison are diverse. Specific capital and operating costs are not given, since too many variables are involved for a meaningful comparison.

8.2 Processing Parameters

Prior to beginning plant design, the known parameters affecting the final product must be taken into consideration. These known parameters vary widely and are summarized in Table 8.1.

Of all the bulk materials produced, aggregates products typically have the lowest price per unit weight. Plant design, however, requires some of the most rugged, massive and expensive equipment in the construction industry. Misjudgments in plant design as a result of poor consideration of the parameters given in Table 8.1 are usually difficult and expensive to correct.

An experienced plant design engineer must carefully evaluate the parameters given in Table 8.1 and formulate valid processing designs. During the information gathering process for establishing parameters, it is essential to maintain good communication. Accurate, factual data are necessary to develop useful, functional parameters. Equally important is the communication of the established parameters to the owner, operator, management, etc. for review prior to proceeding with plant design.

Table 8.1 Parameters Affecting Plant Processing Operations

Pit variations a. Mineralogy b. Effects of drilling and blasting on pit gradation c. Muckpile segregation
Material properties a. Abrasiveness b. Toughness/crushability c. Friability (L.A. abrasion) d. Breakage characteristics e. Dust of fracture f. Deleterious materials g. Specific gravity-relating to volumetric capacity h. Chemistry: relating to type of crushing, iron pyrite stains, etc. i. Flowability/moisture
Potential waste products a. Dust, pond screenings, pit fines b. Economic effect c. Disposal areas and costs
Capital costs
Type of installation: portable, stationary, skid
Operating costs
Design rates
Operating criteria a. Tons per hour operating: capacity b. Percent operating time: reliability c. Percent overtime d. Tons per man-hour/tons per equivalent man-hour e. Kilowatt hours per ton: power utilization f. Wear materials cost per ton g. Regulatory operating restrictions h. Weather considerations
Maintenance considerations
Inventory management
Method of charging plant: truck, loader, excavator
Method of stockpiling: truck, conveyor
Method of storage: open, covered
Method of shipping: truck, rail, barge
Environmental
Space (area) availability; topography
Safety
Future Growth

NOTE: The above guidelines are not all inclusive, but provide general guidance applicable to most plants.

8.3 Project Development

Usually the key parameter that initiates plant design is a favorable market forecast. The market forecast typically covers a minimum of 10 years. Flexibility and fluidity must be planned for as part of the 10-year forecast. The annual volumes and product mix obtained from this forecast are the primary considerations for developing a preliminary flow sheet and plant layout.

The *flow sheet* provides the estimated tons-per-hour flow of processed material moving through the proposed plant. Various crushers reduce the size of the material and screens separate the flow until a usable product is developed. Most flow sheets are completed using some type of computer software. The computer programs serve as a quicker means to compute the output faster and allow making quicker changes. The basic input and output are calculated using generic book capacity ratings and output gradations. Any flow sheet will better predict reality when local experience and knowledge are inserted into the computer calculations. The crushing and screening stations are connected by conveyors and chutes which transport the aggregates to and from processing stations and ultimately to the stockpiles.

Flow Sheets

The flow sheet is often supplemented with operational data. These data include percent of crusher design capacity utilized, screen deck efficiency, conveyor and feeder design capacity, and equipment horsepower requirements. A statement of project scope and a description of material flow usually accompany the flow sheet to facilitate communications. After a flow sheet design is complete, it is cross-checked with the market forecast for balance. The quantitative information in the flow provides a basis for comparison. Balance is obtained by adding and/or deleting equipment until reaching the desired balance (mix) of products. After the flow sheet and market forecast balance, a preliminary physical plant layout is developed. The *plant layout* should be as economical as technically possible, but must address all applicable process parameters.

Review: The completed preliminary flow sheet and plant layout should be reviewed with operating and maintenance personnel. Good communications and the feedback received from their experiences are invaluable toward refining the preliminary flow and plant layout. This interaction may also result in the development of design alternatives as well as lead to acceptance of the design by operating personnel. *Often, the most efficient plant design is developed from use of the operating and maintenance history available from the records of similar existing processing plants and discussions with plant personnel.*

Cost Estimate

With revisions to the plant flow and plant layout completed, a *cost estimate* is developed. The capital construction cost estimate includes all costs related to the plant construction which are to be depreciated. These costs normally include site preparation, design costs, plant equipment (mechanical and electrical), fabrication, installation, buildings, etc. The cost estimate should be accurate and consistent with company capitalization policies. Utilizing an actual history of construction costs to install similar plants is the best approach for developing a cost estimate. When historical data are not available, a standard labor, materials and equipment estimating format should be utilized. The cost to finance the equipment must be considered in the cost estimate process.

The cost estimate should be broken down by processing areas and/or components (e.g., crushing stations, screening stations, conveyors). The cost breakdown is required for clear transmittal to management groups of the spending required. The costs of specific pieces of equipment are required to calculate depreciation. The total estimated cost should be increased by typically 5 to 10 percent to allow for unforeseen contingencies.

Operating Cost Estimate: An *operating cost estimate* includes expenses required to operate the facility once construction is complete. The operating costs typically include personnel, energy consumption, supplies, repairs, overhead, contract services, depreciation and other plant-related operating expenses. Operating cost estimates are customarily derived from operating cost histories of similar facilities or from a detailed itemized cost projection. Operation costs usually are expressed in terms of dollars per ton of aggregates produced or total plant tonnage throughput.

After completion of the cost estimate, project design alternatives should be considered. Clear, concise descriptions and drawings with cost estimates are needed by marketing and capital analysts to compare alternatives. The alternative chosen for the final design should best conform to the overall function for the new system. The final design choice is justified by a quantitative, sound business decision and is not always the most elaborate plant. The role of the design engineer is to provide the appropriate contribution which *best supports the overall function* for the facility being constructed.

Plant Flexibility

Prior to finalizing the design plans of the chosen facility, the plans should be reviewed for flexibility. This review covers the "what if" aspect of the plant flow. Even though the market forecast is a great guide for plant design, it does not cover the surge demand for shipments, changes in pit conditions, washing requirements, varying moisture contents, particle shape and numerous other factors that affect plant production on a daily basis. A practical amount of flexibility should be built into the final plant design to allow the plant to compensate for unplanned factors that adversely affect production. Many times the life expectancy of the aggregates plant is much longer than the sales forecast window. Flexibility built into the design plan will allow the plant to be prepared for future sales.

Inventory Control: A flexible plant provides efficient inventory control and management and deserves special mention. Inventory represents monetary value and should be managed the same as money. Inventories are checked by surveys, production records and monitoring scales. Inventory records aid in scheduling production and provide market size history and seasonal information for sales forecasts.

8.4 Quality Control/Assurance

Definition

Quality control is the process of controlling the quality of the aggregates and encompasses the processing plant design, the techniques implemented in processing, materials handling, stockpiling and loadout. *Quality assurance* is the dependable and accurate monitoring and documentation process to assure that the products shipped meet aggregates specifications. The scope of quality control and quality assurance in this section is limited to the processing plant. A detailed discussion of these aspects is provided in Chapter 16. The gradations, cleanliness and particle shape of the products are controlled in the processing plant. Segregation and degradation of the products are factors to consider in the stockpiling and handling of materials prior to shipping. Older plants may need to be re-configured to add items like surge piles and bins to provide better control for quality purposes.

Sampling and testing the finished product stockpiles and the loadout station are necessary to meet state and other agencies' quality assurance testing requirements and to protect the producer. Many companies have implemented a computerized statistical analysis program to monitor and document their quality assurance program.

In-Plant Testing

The reasons for in-plant testing are first to monitor and then control the variables in the processing plant. Production surges within the crushers and screens can result in wide variations of finished product gradations and therefore must be minimized. Only plants designed with adequate surge piles and surge bins can maintain conditions to achieve optimum production output and desired quality for the various products required.

Gradation Variation: In-plant testing provides information for both controlling quality and increasing productivity. Variations in gradations of finished products may be the result of a plant operating at less than optimum capacity. In many plants the last crushing and screening stage is loaded, or even overloaded, while the crushers and screens upstream are not loaded. Balancing the loading on all the crushers and screens in the circuit to achieve optimum production rates is a major factor in controlling quality and contributes to the goal of the lowest possible operating cost.

A partial list of plant checks include the following:
- Setting of crusher(s)
- Power draw on crusher(s)
- Gradation of feed to crusher(s)
- Gradation of product from crusher(s)
- Throughput in tons per hour of crusher(s)
- Production rate in tons per hour through the plant
- Gradations of the products from the screens

- Operating speed of the crusher(s) and screens
- Amplitude and direction of the operation of the screens

Marginal Materials: Special attention should be given to in-plant testing to address problems associated with processing marginal deposits, such as one resulting in soft particles or a deposit producing undesirable particle shapes (i.e., flat and elongated particles).

Variations in the quality of the products being produced are minimized once the plant is operating at the optimum production rate. A continuous feed must exist as well as the proper close-side crusher settings for the desired product mix. Variations in the aggregates product also can result from segregation or degradation in the stockpile or in the loadout bins.

Segregation

Segregation is defined as the separation of one size of particles from a mass of particles of different sizes. Segregation is caused by the methods used to mix, transport, handle or store the aggregates in the plant under conditions favoring non-random distribution of the aggregates sizes.

Occurrence of Segregation: Segregation starts with the blasting process in the quarry as a result of blasting energy and size distribution of the shot rock in the formation of the muck pile. A wide variation of gradation exists in the quarry run material to be dumped in the primary crusher.

Cone Stockpile: Many aggregates plants stockpile by dumping from a truck and pushing aggregates piles with track-type dozers, rubber tire dozers or front-end loaders. The trend in aggregates plants today is to stockpile with conveyors to minimize the cost of handling aggregates. Tests clearly show that a single cone stockpile results in the highest variation of gradation due to segregation.[1] Figure 8.1 illustrates the segregation that occurs in all primary surge piles.

Segregation occurs with movement and vibration, as is the case when transporting material on the primary conveyor belt as the finer material moves downward to the belt surface. Figure 8.1(a) shows that the primary conveyor trajectory generates a segregating effect as the coarser particles are thrust farther away from the head pulley, while the finer particles drop out closer to the head pulley. As the height of the cone of the surge pile increases, the coarser particles tend to roll and slide to the perimeter of the pile. Segregation becomes more pronounced as the height of stockpile approaches its peak. Degradation of aggregates particles occurs when the aggregates falls a great distance from the conveyor to the stockpile. This can be minimized by keeping the stockpile at a high level or by the use of luffing boom stackers that can be adjusted vertically to control the height of fall.

Material Removal: In Figures 8.1(b) through 8.1(e), the primary plant is not operating, but removal of material from the pile continues. The reclaimed feed to the secondary plant goes from a relatively fine feed to the coarsest feed.

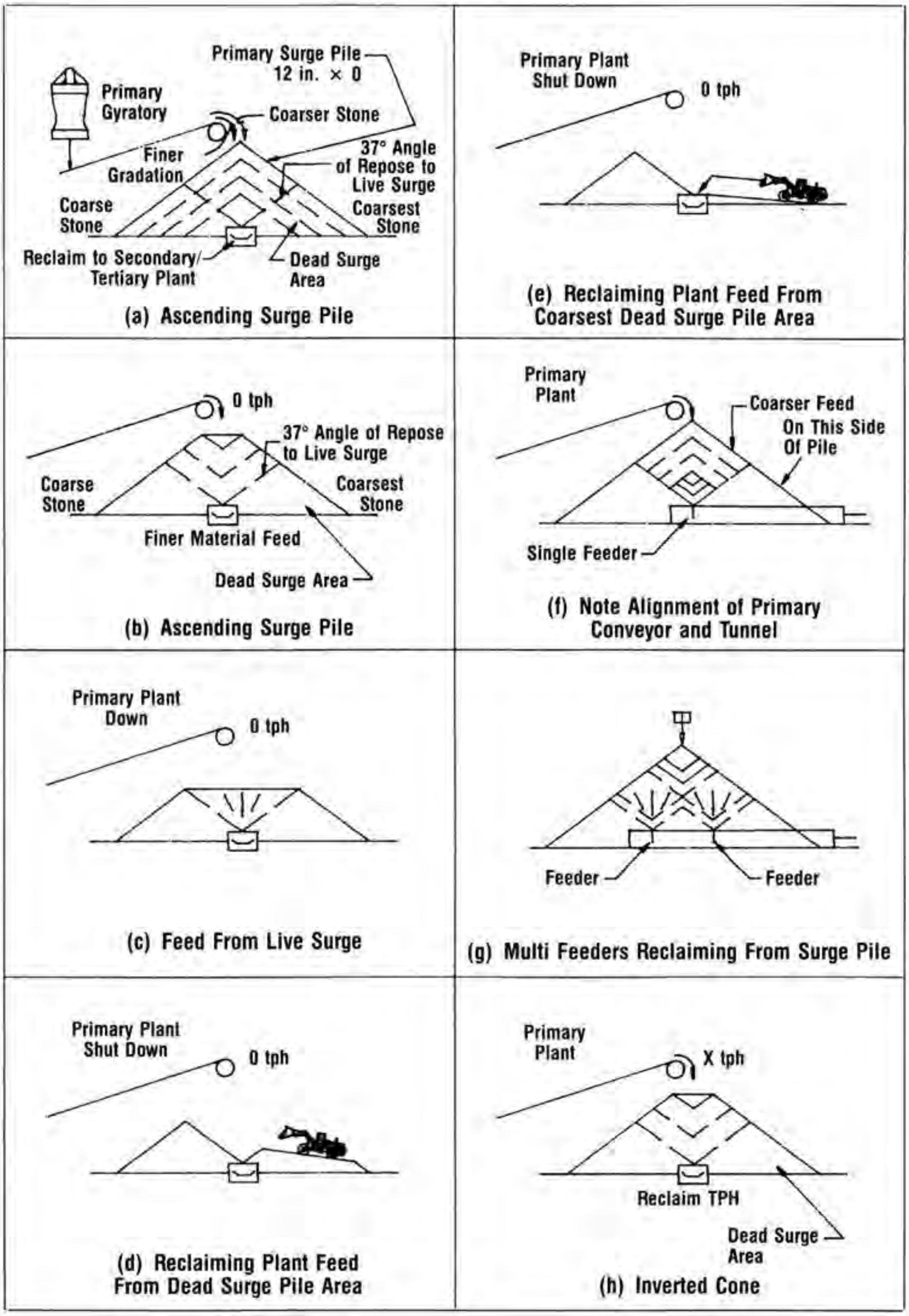


Figure 8.1 Occurrence of segregation in stockpiles

Segregation is controlled much better using the arrangement shown in Figure 8.1(g) and (f). Figure 8.1(g) has a multi-feeder arrangement of the reclaiming tunnel which is at right angles to the conveyor. Figure 8.l (f) has a single feeder arrangement of the reclaiming tunnel which is in line with the primary conveyor.

An inverted cone results when the production from the primary plant is slightly less than or approximately equal to the reclaim rate to the secondary plant, as shown in Figure 8.1(h). This condition results in a more uniform feed to the secondary plant.

The segregation occurring in the intermediate surge pile and finished product stockpile is less than in the primary surge pile because the maximum size has been reduced and the ratio of larger to smaller sizes also has been decreased.

Minimizing Segregation: A *fractionating* plant is designed to provide separate aggregates piles with a given pile having nearly equal aggregates sizes. A fractionating plant is one of the better processing alternatives for controlling segregation. Blending the various size aggregates together at the loadout point, in the asphalt plant, or at the ready mix plant minimizes the effect of segregation and helps achieve the desired product specification. Automated luffing conveyors will minimize the drop height and hence the segregation. The conveyor, working with sensors, allows for the material to be formed into a continuous, non-conical pile. These conveyors are also a key tool in minimizing segregation and promoting overall product quality.

Degradation

Degradation is the breakdown of aggregates into smaller particles. Degradation also can result in dust formation. Bulldozers pushing on coarse aggregates stockpiles and multiple handlings of the aggregates both cause degradation. Although hard rock quarries have limited problems, degradation is a concern in quarries having softer and more friable aggregates. Some aggregates producers compensate for degradation by producing the aggregates slightly on the coarse side of the specifications. Experience and documentation from the in-plant testing program can guide the producer in projecting the degree of degradation resulting from handling the aggregates at the plant and job site.

The Future

In-plant testing is painstaking and time-consuming but necessary. Results can be monitored more closely by strategically locating electronic belt scales and sampling points. Many types and numbers of automatic samplers and particle analyzers are becoming more prevalent. These units provide constant and regular monitoring of the process and the output. Plant automation, discussed in Section 8.15, should be considered. Quality control and quality assurance will become completely integrated into the process by achieving online results from automatic sampling and testing to adjust process control.

8.5 Plant Maintenance

Introduction

This section discusses methods to simplify the ongoing job of plant maintenance including preliminary design considerations, equipment selection for reliability, and standardization of equipment, parts and repair items. Plant maintenance is more than following the manufacturer's recommendations in the equipment manuals, since their guidelines are directed at maintaining only a specific piece of equipment and not the entire plant.

Preventive Maintenance Program

The goal of a plant maintenance program is to ensure equipment reliability. The maintenance program should initially be formulated during the design stage. Preventative maintenance is accomplished through the use of a record-keeping system that documents the history of the problem areas as they develop. Component life expectancy and regular maintenance intervals should be incorporated to avoid untimely and costly emergency breakdowns. This method has been utilized within mobile equipment for years and is now being used within the process industry. A record system allows the operator to predict future time-to-failure for each unit so maintenance can be scheduled before failure occurs. One means of forming a comprehensive maintenance plan is to expand the plan given in individual equipment manuals to cover the other high maintenance areas of the plant. The success of this program depends on how well the plan is documented and followed.

Plant Design Considerations for Maintenance

Drainage: One of the first points to consider is plant drainage. Water trapped in the plant area hinders both the cleanup and maintenance of equipment. For this reason, the best place to locate the plant is at or near the highest point of the property, but this is not always possible. A system of ditches and culverts may be required to divert the runoff away from the plant area.

Access: Each part of the plant must be accessible for maintenance. Platforms and catwalks should be provided where necessary to ensure safe access by maintenance personnel as they inspect and service the equipment.

Crushing Stations: Adequate overhead clearance must be provided for lifting heavy components in and out of the crusher. Work platforms should be designed with sufficient work room around the crusher. Stairs rather than ladders should be designed to access platforms since stairs are safer and easier to use.

Screening Stations: When designing the screening stations, consider how each screen deck is maintained. Access doors should be designed for hoppers and chutes to permit monitoring wear and making repairs. Hoists should be located on the screen's work platforms to carry the screen cloth from the ground to the screen. Handrail design, especially on mobile operations, must be considered to provide access for removal and installation of the various screen decks. The installation of rollaway chutes at the end of the screen should be considered. These chutes can be rolled back for access to the chutes' wear points, the collecting chutes below and the lower decks of the screen. Design the work area around the motor of the screen after the guards are in place to ensure adequate walkway clearance.

Conveyors: Each conveyor should have safe access to the idlers, bearings and drives. Transfer points should be designed sufficiently high off the ground to allow cleanup under them by a front-end loader rather than by a hand shovel. Positioning of belt wipers and belt plows should be placed for easier accessibility and cleanup.

Chutes: By understanding the way material flows, the chutes can be designed to avoid plugging and high wear rates.

Flow Characteristics: The characteristics of the material should be studied to understand how it flows as the gradation changes and as the material changes from a dry to a wet state. This will help determine the minimum slope for the chute design. Usually rock does not flow down a chute unless the chute is sloped at least 37 degree from horizontal. However, this general rule may not apply if the material is either damp or contains a large percentage of fines. In these cases, the slope of the chute may need to be 60 degree or more. The required chute slope can be determined by either field testing or inspection of similar installations.

Transfer Points: A transfer point is a location within the aggregates plant at which a stream of aggregates makes an abrupt change in direction or elevation by being discharged from one conveying device to another. The transfer points should be designed to be as simple as possible and to require a minimum of maintenance. Where possible, rock should flow upon rock. The flow of aggregates discharges on the bed of rock instead of wearing the surface of the chute which eventually requires replacement. Using this principle, *step chutes* can be designed with small incremental steps. The rock builds up in the flat bottom of the steps to a point where only the leading edges and the sides of the chute are exposed to wear, as shown in Figure 8.2.

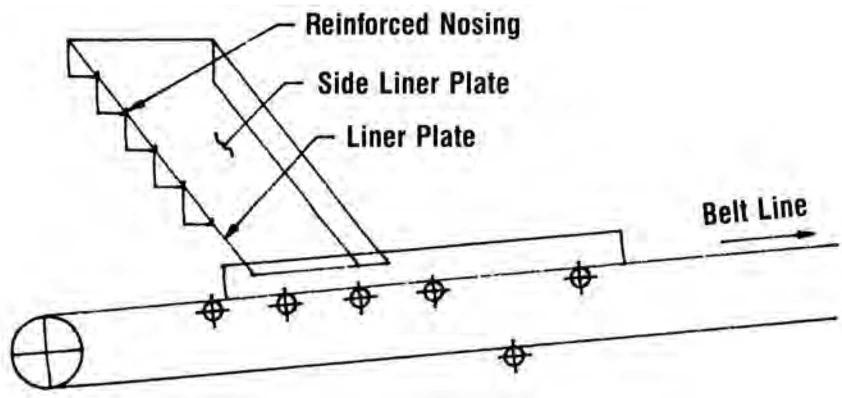


Figure 8.2 Stepped chute with reinforced step nosing and side liner plates.

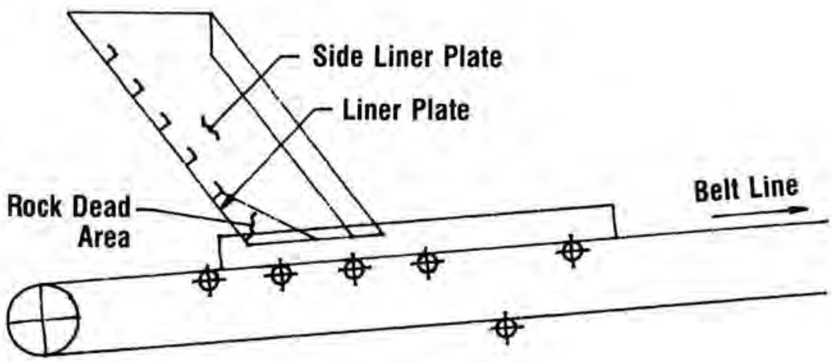


Figure 8.3 Loading chute with built-in stone box to minimize impact on conveyor belt and reduce wear on steel compartments.

An alternate arrangement is to flatten the bottom of the chute and deepen the sides. The rock can then build up to seek its own angle of repose and create the wear surface, as shown in Figure 8.3. In either case, much less effort is required to maintain a rock-on-rock chute than one with a sloped bottom plate.

Special Liners: Unfortunately, the rock-on-rock principle cannot be used everywhere. One such area is in a loadout station where different products are transferred through the same chute. The rock-on-rock principle results in contamination of the finished products, as shown in Figure 8.4. Some producers have had success using various crusher liners in high wear spots. Some have also had success using both metallic and non-metallic, wear-resistant liners. These special liners, such as abrasive resistant steel (AR), offer considerable wear cost savings over mild steel liners. All of these materials are expensive and each item should be investigated before making a purchase.

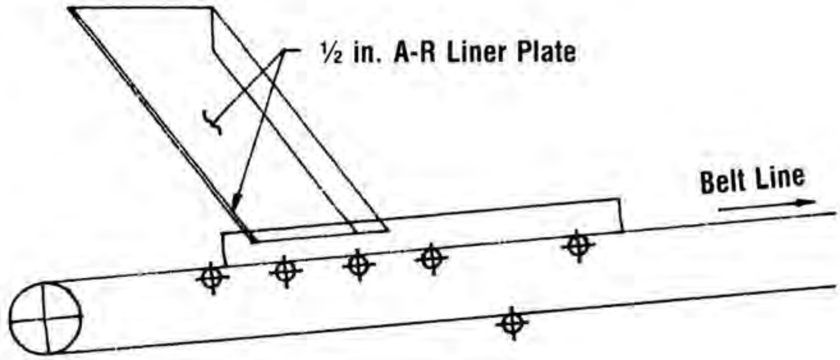


Figure 8.4 Self cleaning chute with ½ inch abrasion-resistant steel liners to combat high wear rate.

Spillage: A discussion on material flow is not complete without addressing spillage. Spillage can occur anywhere during the material handling process. Spillage can be almost eliminated at the transfer points by an effective skirtboard and rubber system on the conveyor, as shown in Figure 8.5. Other items that help reduce spillage are training idlers that keep the belt tracking properly, and belt scrapers that clean the fines from the belt and drop them back into the flow. Make sure the skirting and hopper design includes gathering the material cleaned off the belt by the scraper.

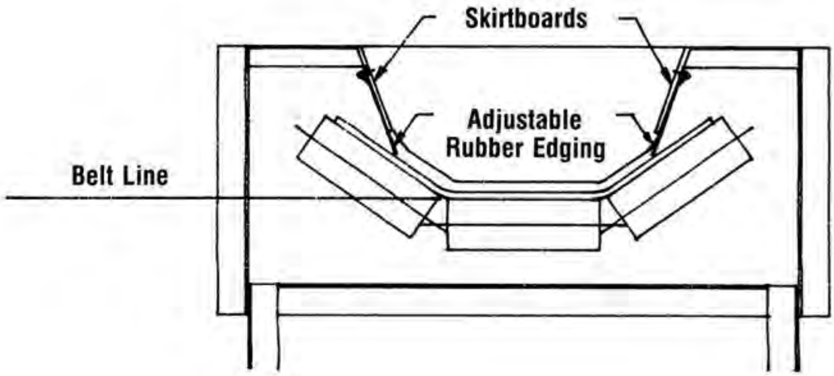


Figure 8.5 Skirtboards for retaining and shaping the material on the conveyor.

Standardization

The degree to which standardization of equipment is applied to an operation depends, in part, upon the effort and imagination given to planning. Standardization should be applied to all parts of the plant. Standardization could involve a decision to buy all units from a single manufacturer for interchangeability of parts. It might also take the form of using only certain sizes of equipment or standardizing components such as bearings. Other areas of standardization to consider include the plant's electrical control components and a uniform painting system. In all cases, the goal of standardization is to simplify maintenance procedures and reduce the required inventory of parts.

For example, only a few chute wear plate sizes might be used throughout the plant. This can save time in making repairs and allow more efficient cutting of wear liners from expensive plate.

However, like any other good idea, standardization can be taken too far. The designer must be aware of the costs and benefits that accompany it. For example, standardization on one particular cone crusher liner to be used in several different crushing stages may not be prudent if each stage has a different set of requirements. Use of the wrong liner can severely restrict the crusher's capacity and reduced liner inventory costs are dwarfed by the cost of lost production.

Summary

The overall appearance of a plant generally reflects its state of maintenance. A clean, well-kept plant is usually one that is in a high state of operating readiness. This high state of readiness does not happen by itself. A significant amount of teamwork and planning is required, but the end result can pay big dividends.

8.6 Crushing Introduction

Rock is broken or crushed when a force is applied with sufficient energy to disrupt internal bonds or planes of weakness which exist within the rock. Crushing rock is an energy-intensive action. The crushed stone operator's ability to influence and control his products lies within the application and control of this energy.

Forces and Breakage

Quarry blasting is the first application of energy to rock in creating a marketable product. Blasting is an important and effective form of crushing. A well-executed blast transforms a solid rock formation into fragments small enough to be accepted by a processing plant. The energy applied, per unit volume of rock blasted, affects the particle size of rock in the resulting shot rock or *muck* pile. Half of the rock blasted is frequently smaller than 8 inches. A low energy or poorly executed blast results in many oversize pieces which require extensive secondary breakage.

Required Energy: The quantity of energy applied to a unit of stone relates directly to the amount of size reduction accomplished. This is true for mechanical crushing as well as for blasting. The amount of power required in any given crushing device is basically a function of three factors:

1. Material's resistance to being crushed: Various laboratory tests are available which yield a crushing resistance factor.[2]

2. Amount of size-reduction taking place: The term reduction ratio is used to define the ratio of crusher feed size to product size. The reduction ratio can be taken as the ratio of the largest pieces in both feed and product, but it is more accurately expressed using a size corresponding to 80 percent passing for each gradation considered.
3. The quantity of material undergoing the crushing work per unit of time, such as tons per hour.

Stage Crushing: Concentrating a crusher's available power on a high-reduction ratio can result in the generation of excessive fines due to over breakage. The objective of crushing in aggregates production is size reduction to a specified size-range. Producers are usually sensitive to excessive generation of fines. *Therefore, controlling the degree of breakage by spreading reduction over three or more stages of crushing and screening sequences, i.e., crushing stages, is an important concept.* Consider breaking a block of stone to produce as many 1-inch cubes as possible from this block. A small hammer and chisel are certainly more effective than a large sledge hammer. Understanding the reduction capability of each type of crushing machine coupled with the specific material to be reduced will help to determine how many stages each plant will require. The more work, or reduction, that can be done earlier in the operation will provide greater plant throughput capacity and lower overall fines production.

Fracture Mechanisms and Crusher Type: Although the quantity of energy applied to a unit of rock determines the amount of size reduction, the application rate of that energy has a major influence on how individual particles are broken. Particles break from three major causes: abrasion, cleavage and shatter, as shown in Figure 8.6. The description of each method of fracture in this figure relates to the increasing intensity of crushing energy. All these fracture events occur to some degree in all commercial crushers. However, different types of crushing machines cause specific types of fractures. Impact crushers, which exert high-speed blows, cause a high degree of shatter. Compression-type machines of the jaw and gyratory style apply their energy much more slowly, creating abrasion and cleavage. Cone-type compression crushers have a reciprocating cycle approximately twice that of jaw or gyratory machines and accentuate both cleavage and shatter.

Resulting Gradations: Figure 8.7 shows a probable product size distribution resulting from abrasion, cleavage and shatter fractures. A producer might be able to use these characteristic breakage patterns to aid in the production of needed product sizes.

Productive Use of Crushing Power: The breakage environment is important to the productive use of crushing power. As particles are stressed to the breaking point, they absorb a considerable amount of energy. Broken pieces of particles release energy by flying off in all directions. It is important to operate crushers near full load for this kinetic energy to efficiently be used to break other particles and re-break themselves. Deteriorated foundations under crushers are partial evidence of the considerable energy released as broken rock discharges from the crusher.

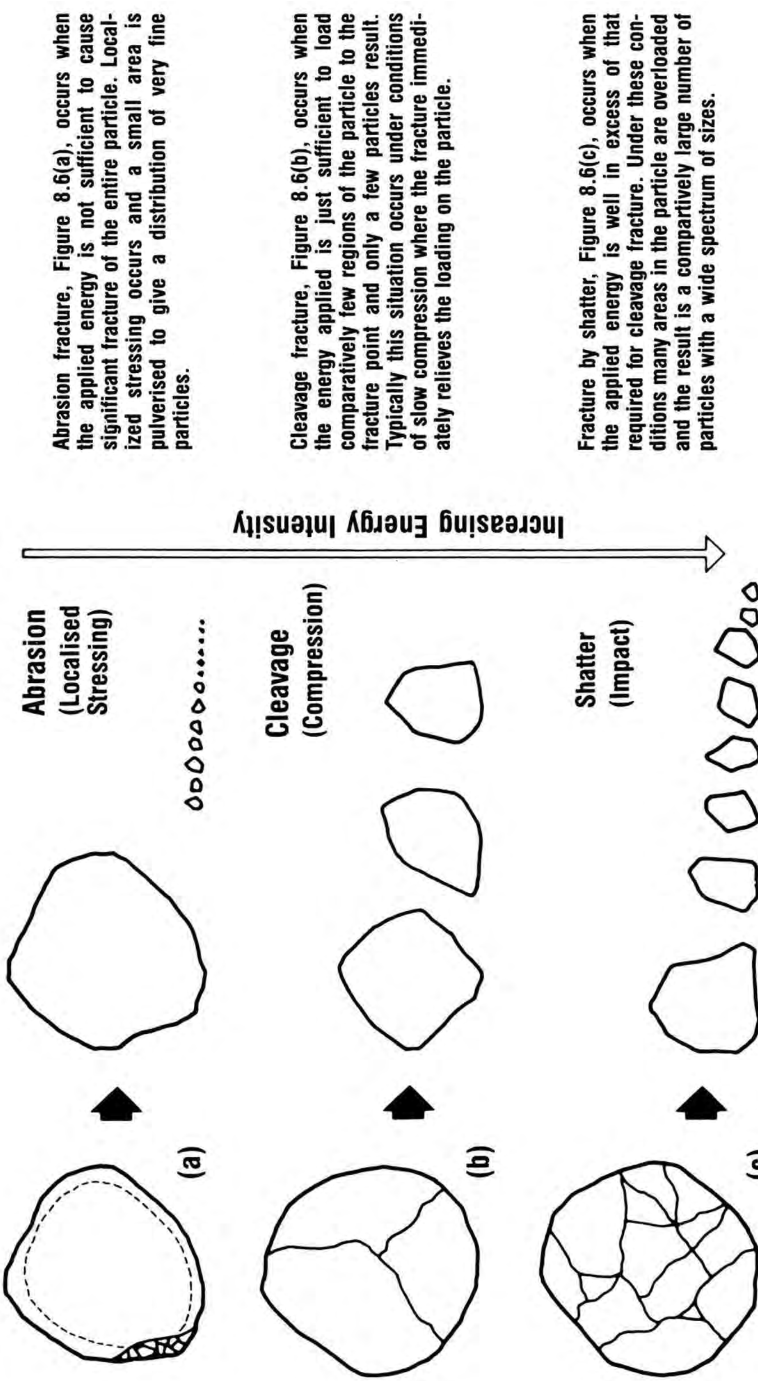


Figure 8.6 Abrasion, clevage and shatter mechanisms of rock breakage.[3]

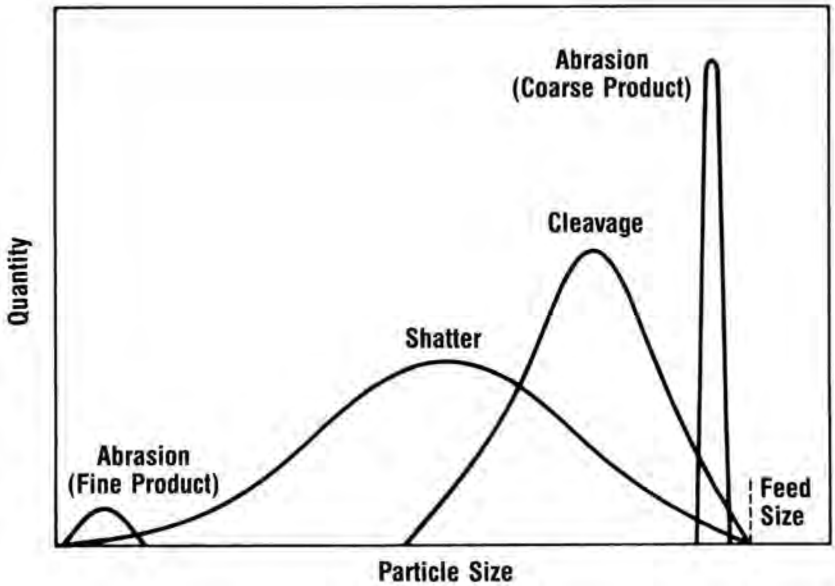


Figure 8.7 Representation of the mechanisms of particle fracture and the resulting product size distributions.[3]

Crushing Equipment

Jaw, gyratory, cone and roll crushers are compression-type machines that apply a compressive force to rock trapped between their crushing surfaces. Differences in size, crushing chamber configuration, speed and action make compression crushers suitable for different applications. A common characteristic of compression-type machines is that the product must pass through a fixed *but adjustable* opening before being discharged. Power demand, volume of stone processed and product control are all influenced by the discharge opening.

Impact crushers, the other major type of machine, apply a high speed impact force to the feed rock. Rebounding between particles and against machine surfaces further takes advantage of the energy from the initial hit. Some impact machines use close-fitting discharge bars or grates to further shear or grind particles between the rotating and stationary parts. A common characteristic of impact-type crushers is that the energy available for impact varies as the square of rotational speed, and the amount of energy that a particle can absorb is based on its mass and stiffness. Large particles break more readily from impact than small particles. Impact crushers require some means of feed rate control in order to control power demand.

Many of the major types of crushers are shown in Table 8.2, with comments on their characteristics and typical applications.

Table 8.2 Seleted Major Types of Crushers[3]

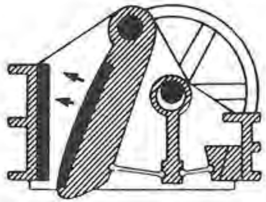
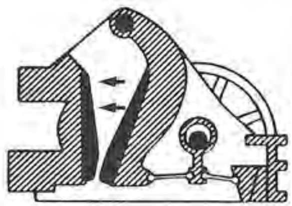
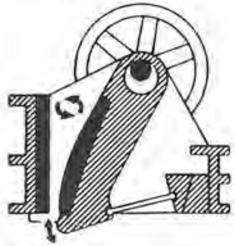
Type			Illustration	Reduction Ratio	Characteristics & Applications
Jaw Crushers	Double Toggle	Blake		Average 7:1 Range 4:1 to 9:1	Earliest practical jaw crusher patented in 1858 by Eli Whitney Blake. Large energy storing flywheels, high mechanical advantage and pivoted jaw motion makes this design suitable for primary reduction of hard, tough, abrasive rock. Fairly slow speed, but large stroke at discharge and conservative nip angle produce good capacity with difficult rock. Usually rated at open-side setting.
Jaw Crushers	Double Toggle	Overhead Pivot		Average 7:1 Range 4:1 to 9:1	Similar to Blake, but with swing jaw pivot located over the center line of the crushing chamber, creates more stroke at the feed opening and a motion more perpendicular to the stationary jaw. Higher speed with smaller stroke produces similar capacity to Blake. May require lower power due to action. Latest designs locate upper jaw arms outside the frame to increase vertical feed opening.
Jaw Crushers	Single Toggle	Overhead Eccentric		Average 7:1 Range 4:1 to 9:1	The moveable jaw is supported at the top by the driven shaft. The eccentric shaft imparts a circular motion to the jaw at the feed entrance, converting to an elipitical, nearly horizontal motion at the discharge by pivoting on the toggle. Large, aggressive top motion and downward vertical motion component encourages feed entrance and capacity; however, it also increases abrasive action and transmits crushing shocks directed to the bearings. Best suited to less abrasive, more friable rocks, but improved materials and designs are increasing its range of application. Capacity is usually rated at close side setting.

Table 8.2 Seleted Major Types of Crushers[3] (continued)

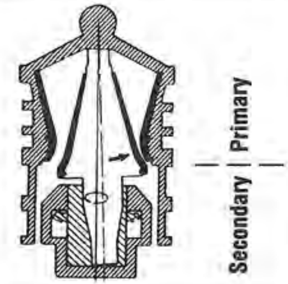
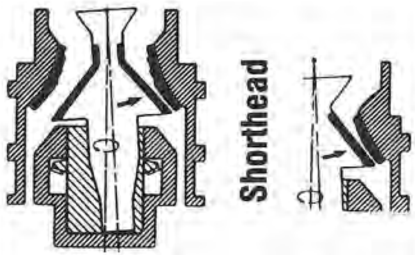
Type			Illustration	Reduction Ratio	Characteristics & Applications
Gyratory Crushers	True	Primary & Secondary		Average 8:1 Range 3:1 to 10:1	Primary: Characterized by diverging conical crushing surfaces formed by a gyrating mantle within a deep bowl, it provides continuous crushing action for high capacity primary or secondary crushing of hard tough abrasive rock. Trucks may dump directly into the cavity. Is able to handle slabby feeds better than jaw crushers and produce a more cubical product through the annualar discharge opening. Capacity is usually rated at open-side setting.
				Average 4:1	Secondary: Used to reduce 8-in. to 12-in. material down to 3-in. to 4-in. The feed is normally scalped ahead.
	Cone	Standard		4:1 to 6:1	Cone gyratories operate at about twice the speed and with a much larger head movement than true gyratories. A relatively flat gyrating head forms a crushing chamber within an inverted bowl. The large head throw and speed creates an impact like crushing action. "Standard" versions are made with large feed openings for secondary applications making products in the 1-in. to 4-in. range. "Shorthead" versions have smaller feed openings and a shorter, steeper, more parallel crushing chamber suitable for products ranging from ⅛-in. to 1-in. Both crushers are suitable for hard, tough abrasive crushing applications. Capacity is usually rated at closed-side setting.
		Attrition		2:1 to 5:1	For production of fine sizes (¼ in. top size or less). Shallow cone angle of 25° to the horizontal and multilayer impact plus attrition results in a cubical product with relatively low liner wear. A controlled choke feed is mandatory. The finer the product, the higher the recirculating load. Not suitable for sticky feed. Usually mounted in a closed circuit system. Finished product capacity may not be related to the closed-side crusher setting.

Table 8.2 Seleted Major Types of Crushers[3] (continued)

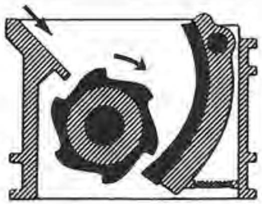
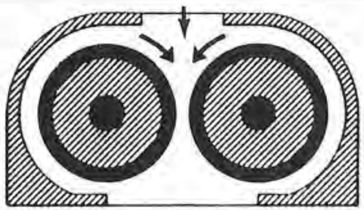
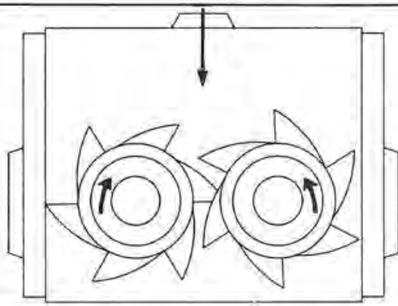
Type			Illustration	Reduction Ratio	Characteristics & Applications
Roll Crushers	Compression	Single Roll		Max. 7:1	Because the feed is dragged against a liner, economical only for low abrasion feeds. Can handle sticky materials.
		Double Roll		Max. 3:1	With a relatively low reduction ratio, produces a high proportion of product near the setting with a minimum of fines. Can handle sticky feeds.
	Shear	Double Shaft		Max. 5:1	Has two rolls with picks similar to feeder-breaker and is used in similar applications. Its advantages over the feed-breaker include the absence of a drag chain and the ability to pass undersize feed at a very high rate.

Table 8.2 Seleted Major Types of Crushers[3] (continued)

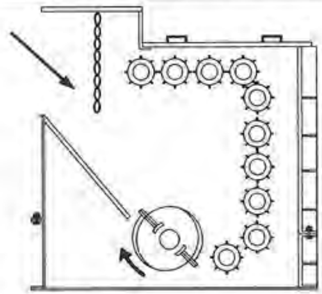
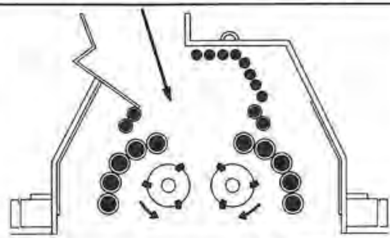
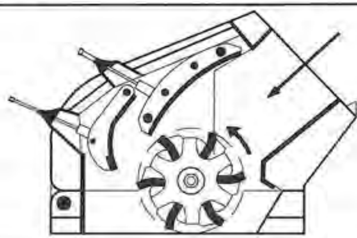
Type			Illustration	Reduction Ratio	Characteristics & Applications
Impact Crushers	Horizontal Shaft Primary	Single Rotor		to 15:1	Breaks mostly by impact, giving a high reduction ratio and a cubical product. Reduction ratio can be increased with higher speeds and/or closer clearances but at the cost of greater wear. Economical use is limited to low abrasion feeds. Suitable for damp and/or moderately sticky feeds.
		Double Rotor		to 15:1	Similar to single rotor machines and may make a somewhat higher proportion of fines.
		Andreas		to 15:1	The geometry of the impact aprons gives a high proportion of impact crushing, which results in lower wear costs for a given feed compared to other impact crushers. The gap settings of the aprons are easier to change than other impact crushers, which allows better control of the reduction ratio.

Table 8.2 Seleted Major Types of Crushers[3] (continued)

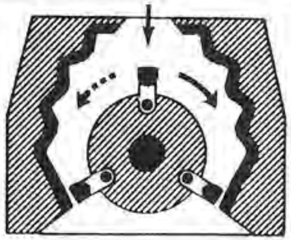
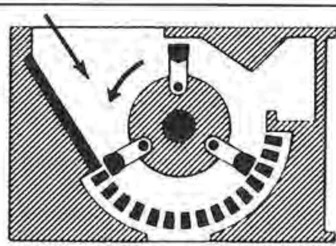
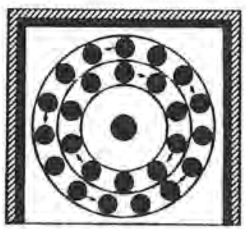
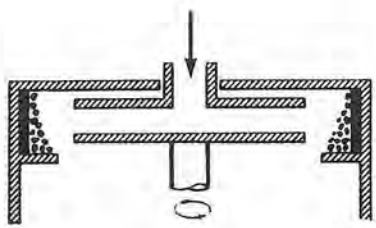
Type			Illustration	Reduction Ratio	Characteristics & Applications
Impact Crushers	Horizontal Shaft—Secondary and Tertiary	Reversible		to 15:1	Gives high reduction ratio and a cubical product, similar to other impactors. Manganese hammers increase maintenance costs on higher abrasive feeds.
		Hammer Mill		to 20:1	Crushing by attrition as well as impact. Produces a cubical product with a high proportion of fines. Economical use is limited to low abrasive feed. Cannot tolerate wet or sticky feed which would clog the grate openings.
		Cage Mill		8:1 to 20:1	May have 1, 2, 4 or 6 cages with alternate rows of pins turning the opposite direction. Feed enters at the center and is thrown outward into successively faster spinning rows of pins. Most suitable for low abrasive, dry feed.

Table 8.2 Seleted Major Types of Crushers[3] (continued)

Type			Illustration	Reduction Ratio	Characteristics & Applications
Impact Crushers	Vertical Shaft—Secondaries	Anvil		to 4:1	Feed is thrown centrifugally by shoes against a ring of anvils set at right angles to the flow. Usually employed in a tertiary or quaternary application to produce a cubical, fine product. Can continue to effect a reduction on feed finer than that which a horizontal shaft impactor (−½ in.) but at a higher maintenance cost because of the sliding wear on the impeller shoes.
		Autogeneous	 Typical	to 3:1	Similar to the anvil machine except that the feed material slides against rock on the table and strikes a pocket of rock around the circumference. Suited for abrasive material if it is friable. Lower wear but lower capacity and higher energy cost than anvil machines.
		Combination		to 4:1	When an abrasive material is not friable, a rock-on-rock impeller may be combined with a ring of anvils to improve capacity and reduction ratio.

Predicting Crusher Performance

Crusher manufacturers provide technical literature outlining the factors influencing performance of their machines. Manufacturers' capacity and gradation charts allow rough selection of the equipment sizes that users may require. However, rocks exhibit unique characteristics governing their reaction to crushing. Manufacturers' charts cannot fully account for the many different physical and chemical structures potentially encountered and as a result for how the crusher is ultimately applied.[9]

The feed size and input gradation to crushers influences their capacity and product analysis, but rarely is factored into manufacturers' production charts. Also, even normal wear to crushing surfaces can have dramatic effects on crusher performance. Crushing abrasive stone requires frequent performance tests to confirm that operating parameters are within acceptable limits.

Optimum Feed: An often overlooked influence on crusher performance is the degree to which its capacity is utilized. Most crushing equipment depends on the interaction of particles in the crushing chamber. An underfed compression machine allows passage of oversize particles that would normally be retained in the crusher by other particles being processed and as a result is crushed to the size desired. Both impact and compression machines depend upon inter-particle energy transfer to achieve their most efficient performance levels. The old saying "make sure crushers are large enough to handle all surge conditions," results in reduced performance when crushers are underfed.

Application Assistance: Equipment manufacturers typically provide application assistance when equipment performance does not meet published expectations or when special product demands challenge traditional applications. Many operate laboratories to test and confirm machine performance by crushing feed samples provided by potential users. Other users often are willing to share their experience and performance data with potential new users.

Basic Factors Influencing Crushed Product Characteristics

The object of crushing for aggregates product is size reduction to a specified size range of well-shaped particles and a minimum production of unwanted finer particles.

Fines Generation: Any crushing event generates a range of product sizes from fine to coarse. The proportion of sizes produced within a given machine is related to the reduction ratio. Crushers operated at high reduction ratios are likely to over-crush desired product before coarser particles can be sorted out as product. Where minimum fines are a requirement, crushers should be operated at low reduction ratios in closed circuit with a product separating screen sized to handle the circulating load. The rock recirculated to the crusher will be smaller than the original feed, further reducing the overall reduction ratio within the crusher.

Impac-type crushers usually produce a higher percentage of minus No. 4 sieve size material than compression-type machines when both are set to produce similar coarse products.

However, the grading of the fines fraction alone often shows that the compression machine creates finer particles. Fines produced by abrasion reduction are characteristic of compression machines, whereas pure impact reduction is less effective as the mass of particles decreases. The effect of pure impact upon a free body of material varies directly with the mass of the body. High speed and/or discharge grates are required for impact machines to generate fine particles.

Diminished Product Yield: Any action that breaks rock into smaller pieces than a target size irrevocably diminishes product yield. Compression machines have the useful characteristic of accentuating the quantity of particle sizes near the close-side setting dimension of the crusher. This is because the compression stroke ends at a predetermined setting, releasing already sized material to pass without further crushing. This phenomenon is influenced by reduction ratio, speed and throw of the crushing head, and crushing chamber configuration. Equipment manufacturers should be consulted for more specific information. The *close-side* setting is the width of the smallest opening between the crushing surfaces through which aggregates must pass.

Tuning Impact Crushers: Impact crushers can be tuned by speed, impact bar spacing, throw distance and/or grate spacing to emphasize certain sizes. However, the impact process by nature is less discriminate than a controlled stroke process.

Particle Shape: Shergold[4] conducted a study of nearly five years of 10 crushers operating under controlled conditions with 12 different types of rock. Conclusions reached concerning factors affecting the particle shape of a product include:

1. "The reduction ratio suffered by any particle in the crushed product is the ratio of the size of the piece of rock from which it was broken to the size of the given particle.
2. "It has been shown in this paper that the dominant factor deciding the particle shape of a crushed product was the reduction ratio as defined in (1) above. Although its effect was sometimes complicated by re-crushing in the lower part of the crusher cavity, it can in general be said that:
   a. A larger-sized feed gave a poorer-shaped product.
   b. The smaller sizes in any given product generally had a poorer shape than the larger sizes, but the size of chipping (¾-inch by ½-inch) present in the product in the greatest proportion generally had the best shape.
3. "The effect of the type of granulator (i.e., crusher) on the shape of the product was not as great as the effect of the reduction ratio. The order of merit of the different types of granulator in this respect was:
   - Impact breaker with unrestricted outlet
   - Impact breaker with restricted outlet
   - Jaw granulator
   - Crushing rolls
   - Cone granulator

   Careful hand-breaking gave no better shape than a jaw granulator and not as good a shape as an impact breaker.

4. "It is thought that the good particle shape obtained with impact breakers can be explained by the assumption that, in impact breaking, the stresses have a more or less random distribution, whereas in compressive crushing the stresses are concentrated in relatively closely spaced planes near the surface. Some types of rock produced better shape products than others, the differences being the same order as those between the different types of machines. No precise relations were found between the type of rock and the grained rock to give a poorer-shaped product.
5. "Slightly poorer-shaped products resulted from the following factors, most of which could be explained by the assumption that less re-crushing took place, resulting in an increase in the average reduction ratio:
   - Slower rates of feed (except impact breakers)
   - Worn hammers on an impact breaker
   - Dry feeds, which gave a slightly poorer-shaped product than moist feeds
   - Cubicle feeds, which gave a slightly poorer-shaped product than flaky feeds
6. "Closed-circuit crushing would give a slightly better-shaped product than open-circuit crushing, the extent of the improvement depending on the proportion of material fed back for re-crushing.
7. "When crushing a feed of 3-inch maximum size of any of the 12 different types of rock used, it was possible to obtain ¾-inch and ½-inch chippings complying with the British Standard requirement for a maximum flakiness index 3 of 35 from any of the 10 different machines, but for the ⅜-inch chippings the impact breakers were the only machines that consistently gave a product within this limit."

8.7 Screening

Screening is the separation of aggregates particles into various sizes. Types of screens used to separate aggregates include vibrating inclined, stationery inclined, vibrating grizzly, vibrating horizontal and rotary.

Vibrating Inclined Screen: The *vibrating inclined screen* is the most popular of the screen types. Types of vibrating screens include those with two and four bearings, high-speed screens and screens which vibrate at the natural frequency of selected spring clusters. The majority of aggregates producers utilize a two- or three-deck inclined vibrating screen with two bearings, as illustrated in Figure 8.8. The two bearing, circle throw, inclined screen utilizes a counterweight on a shaft to move the screen through approximately a ⅜-inch displacement throw. Screen throw varies inversely with the shaft speed which ranges from 800 to 950 rpm. The screen is isolated on springs and is customarily powered by an electric motor with a V-belt drive. Screen slopes vary from 15° to 30° for dry separations to slightly flatter slopes for wet sieving.

The inclined vibrating screen is easily adjusted to improve efficiency. Variations in slope, speed, stroke and direction of rotation provide the flexibility required to determine the best combination of variables for making the separation, as shown in Table 8.3 and Figure 8.9.

While the two bearing single shaft inclined screen remains the most popular, dual or triple shaft machines have continued to gain in popularity. As production levels have increased so have the screen sizes. Larger screens require more vibrator mass to move both the larger boxes as well as the increased amount of aggregates material to be separated.

Reliability: The inclined vibrating screen has proved to be the most reliable screen for aggregates separation. The addition of extra counterweights, allow the screen to handle dense, coarse aggregates. When properly sized, the inclined vibrating screen performs virtually maintenance free except for wear from the aggregates as it is processed. Horizontal screens normally are selected when conserving headroom or there is a need to maintain a lower profile. Variations in speed and stroke required for the separation are illustrated in Table 8.4.

Horizontal Screens: The horizontal screen, once thought of only for portability reasons also has found greater market application. Tighter aggregates specifications have turned some producers to look at horizontal screens to increase their plant efficiency. Two and three shaft machines operating at ⅜- to ¾-inch stroke are being utilized to make critical cuts in aggregates operation. It is best to determine which type of screen fits the distinct application. It may be possible to design a plant with both inclined and horizontal screens within the same operation.

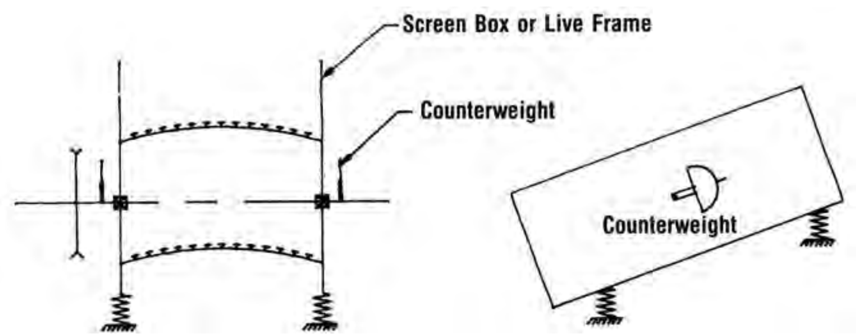


Figure 8.8 Two bearing circle throw (unbalanced pulley) inclined screens.[5]

Table 8.3 Stroke Speed and Slope Selection for Inclined Screens for Dry 100 pot Material and Flow Mechanism Rotation[5]

Stroke (in.)	Nominal Speed (RPM)	Top Deck Opening: 35 M To 50 M	20 M To 35 M	10 M To 20 M	4 M To 10 M	½ in. To 4 M	1 in. To ½ in.	2 in. To 1 in.	3 in. To 2 in.	4 in. To 3 in.	6 in. To 4 in.	8 in. To 6 in.	Above 8 in.	Slope Range (degree)
03	3500	Preferred	Acceptable											24-30
05	2600	Acceptable	Preferred	Preferred										24-30
06	2100	Acceptable	Preferred	Preferred	Acceptable									22-28
3/32	1800		Acceptable	Preferred	Preferred	Acceptable								22-26
1/8	1600		Acceptable	Preferred	Preferred	Acceptable								22-26
3/6	1400			Acceptable	Preferred	Preferred	Acceptable							20-25
1/4	1000			Acceptable	Preferred	Preferred	Acceptable							18-25
5/16	900					Preferred	Preferred	Preferred						18-25
3/8	850					Acceptable	Preferred	Preferred	Preferred	Preferred				18-25
7/16	750								Acceptable	Preferred	Preferred			18-25
1/2	700										Acceptable	Preferred	Preferred	18-25

Preferred (cross-hatched bar) Acceptable (vertical-bar pattern) M = mesh

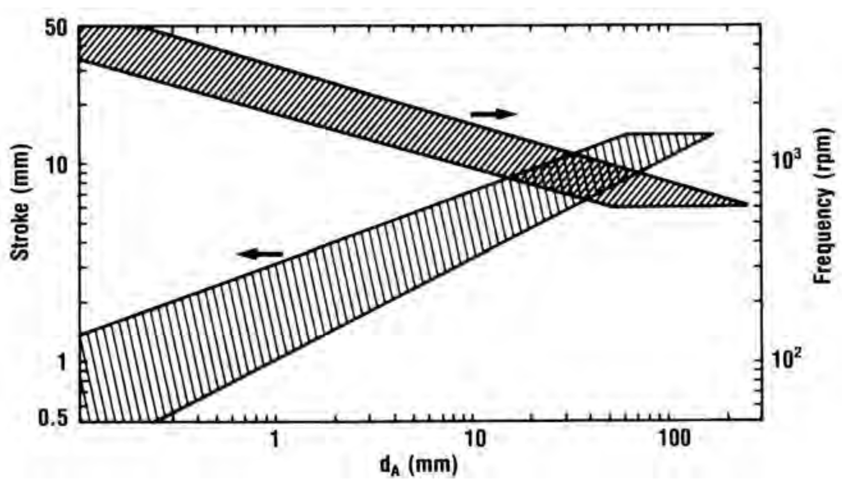


Figure 8.9 Recommended strokes and frequencies for inclined and horizontal vibrating screens.[3]

Table 8.4 Stroke & Speed Selection for Horizontal Screens for Dry 100 pcf Material[3]

Stroke (in.)	Nominal Speed (RPM)	Top Deck Opening: Less Than 10 M	4 M To 10 M	½ in. To 4 M	1 in. To ½ in.	2 in. To 1 in.	4 in. To 2 in.
3/8	950	Consult Manufacturer	Preferred	Preferred	Acceptable		
7/16	900	Consult Manufacturer	Acceptable	Preferred	Preferred		
1/2	850	Consult Manufacturer		Acceptable	Preferred	Preferred	
5/8	800	Consult Manufacturer		Acceptable	Acceptable	Preferred	Preferred
3/4	750	Consult Manufacturer			Acceptable	Acceptable	Preferred

Preferred XXXX Acceptable IIIII M = mesh

Screening Media: The screening surface must be strong enough to support the weight of the material, be flexible enough to withstand the vibration and provide enough open area to allow the desired through-put of aggregates. A variety of screen surface sizes, shapes, types and materials available often are manufactured with unique variations. The screen surface manufacturer's catalogs contain a great deal of information to aid in selecting a screen surface. Each surface selection is unique and frequently requires trial and error to obtain the appropriate screen surface.

Wire Cloth: Woven wire cloth is the most commonly used and versatile screening media in the aggregates industry. Aggregates plants utilize the woven wire to scalp, size and de-water. The open area of woven wire cloth is the single most important factor governing the effectiveness of the cloth to separate. Matching the open area against the wire diameter best suited for maximum life permits selection of the optimum cloth. In practice, open area varies from 20 to 80 percent of the total screen area.

Woven wire cloth is available in two basic configurations: square and rectangular. Square openings commonly are used in the aggregates industry and provide the most accurate separations. Rectangular openings provide better service under certain operating conditions. Short slot and long slot configurations of rectangular openings are both available. The short slot configuration has a length-to-width ratio of approximately four and utilizes a larger wire diameter to increase service life while maintaining the same percent of open deck area. Short slot configurations typically reduce blinding and clogging, but perform poorly when scalping flat and elongated aggregates.

The long slot configuration utilizes cluster-woven slots that are 1- to 6-inches long and exceed four times their width. The long wires of the cluster actually develop a secondary motion which helps alleviate plugging and sticking. The secondary motion is particularly advantageous when screening near size or moist aggregates. The long slot configuration usually has a shorter service life than a short slot screen due to the secondary motion causing early failure of the long wires. Rectangular openings are ordinarily orientated with their long dimension parallel with

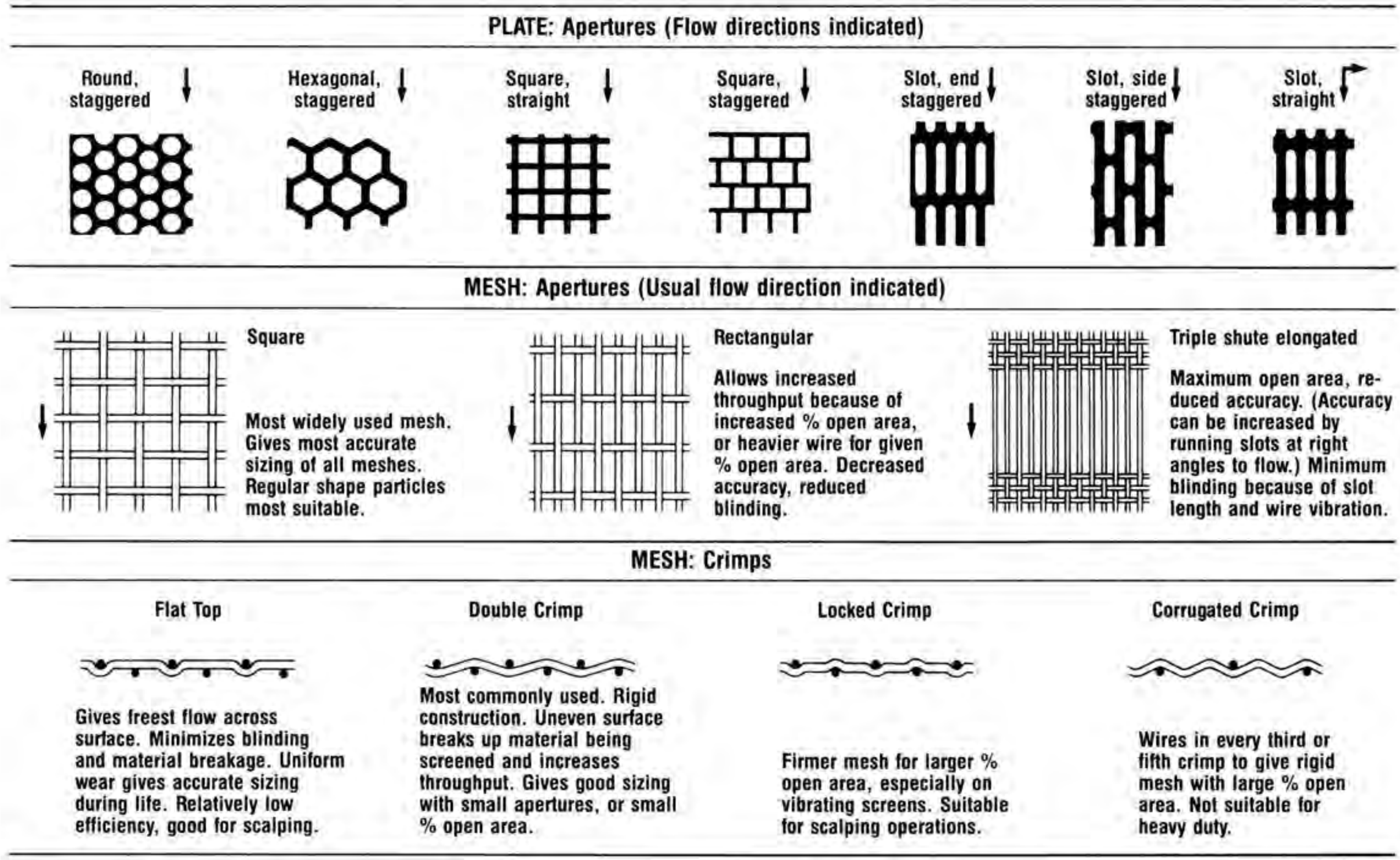


Figure 8.10 Screen surfaces.[3]

Table 8.5 Screening Area Formula[3]

A separate calculation is required for each deck of a multiple deck screen. The following formula is used in each calculation:

$$\text{Screening Area (ft}^2) = \frac{U}{A \times B \times C \times D \times E \times F \times G \times H \times I}$$

U = Undersize Factor	Amount in tons per hour of material in feed to screen surface (deck) that is smaller than a specified aperture.
A = Basic Capacity Factor	Predetermined rate of material in tons per hour through a square foot of a specified opening when feed to deck contains 25% oversize (Factor B) and 40% halfsize (Factor C).
B = Oversize Factor	Actual percent of material in feed to deck that is larger than a specified aperture (Adjusts Factor A to suit conditions.)
C = Halfsize Factor	Actual percent of material in feed to deck that is one-half the size of a specified aperture. (Adjusts Factor A to suit conditions.)
D = Deck Location Factor	Applies to multiple deck screens. Total screening area is available for top deck separation. Time delay for material to pass through deck and leaves less effective area available on next deck. This factor is expressed in a percent of top deck effective areas.
E = Wet Screening Factor	Applies when water is sprayed on the material as it moves down the screening deck. Generally, about 5 to 7 gpm of water are used per ton per hour of solids fed to the screen. A sufficient volume of water should be supplied so that a portion can be combined with the solids into a feed box to prepare a slurry feed to the screen. The balance of water is added through a series of spray bars located over the screening deck.
F = Material Weight Factor	The bulk density of the material being seived in pounds per cubic foot and divide by 100.
G = Screen Surface Open Area Factor	Applies when open area of screening surface is less than open area shown in Factor "A" capacity chart. Open area of screen surface being used. Open area indicated on capacity chart.
H = Shape of Opening Factor	Applies when rectangular openings are used. Slotted or oblong openings will pass more material per square foot than square openings.
I = Efficiency Factor	Applies when objective screening efficiency is less than 95%.

NOTE: The required tables and examples to utilize the above formula are given elsewhere.[3]

material flow to maximize throughout. To minimize the passage of flat and elongated particles, the rectangular openings are installed with their long dimension perpendicular to the material flow. The configuration of the surface of the screening is available in a variety of shapes, as illustrated by Figure 8.10.

The wire used in woven wire cloth is available in a number of alloys including stainless steel. The different alloys provide additional abrasion resistance or reduce blinding, sticking and corrosion. The weaving of the many wire types into cloth is performed on various looms depending on opening and wire diameter requirements.

Other Types of Screening Surfaces: Other types of screening medium used in the aggregates industry include rubber, polyurethane, perforated plate, rubber-clad perforated plate, grizzly bars and piano wire. The grizzly bars and perforated plate are of rugged construction and can withstand great abuse when used in heavy scalping applications. Rubber and polyurethane are typically employed in high wear areas to increase service life. Rubber and polyurethane also help reduce noise and decrease blinding by flexing the aperture that can be tapered outward from the top. Piano wire screening is used to separate damp and/or fine aggregates. Damp, fine aggregates are the most difficult product to process.

Screen Type and Size: Selection of an appropriate type and size of screening unit is important. An aggregates plant with inadequate screening capacity limits the plant's production rate and increases the difficulty of producing consistent products. Operating costs will be high since other portions of the plant will be working at less than capacity to accommodate the screening unit's limitations. Table 8.5 presents an equation recommended by the Vibrating Screen Manufacturers Association for determination of required screen area.[8]

Screen Performance: Screen performance is controlled by the screen capacity and efficiency. Screen capacity is defined as the number of tons per hour of aggregates being fed to the screen. Capacity is almost directly proportional to the screen width. Since increasing capacity usually results in decreased efficiency, the two criteria should always be stated together when referring to a screen. Increasing the length of a screen provides more opportunity for aggregates throughput, thus increasing the efficiency but results in little capacity increase, as illustrated in Figure 8.11. Normally, an aggregates screen has a length of two to three times its width. Under special circumstances, such as space restrictions, the length-to-width ratio is customized to fit the application.

Screen Efficiency: Screening efficiency is defined as the percent of undersize which actually passes a screening deck. A screen efficiency of 100 percent is not practical to attain. A screen efficiency of 90 to 95 percent is typical for sizing in the aggregates industry. Most aggregates specifications are written to accommodate the inefficiency in the screening process. For scalping and crusher relief, removing aggregates finer than the crusher product prior to entering the crusher, an efficiency of 75 to 85 percent generally is accepted since the final sizing is performed later in the plant.

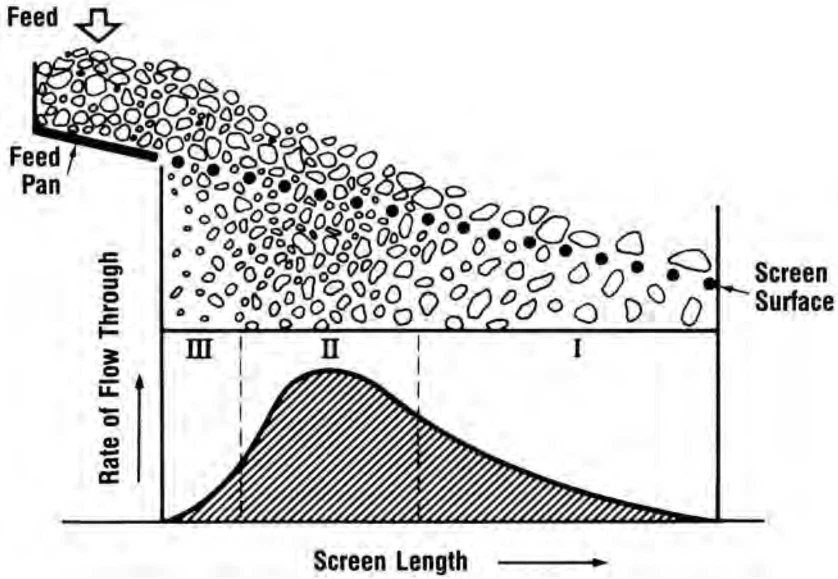


Figure 8.11 The three major regions occurring along a screening surface.[3]

Multiple Deck Screens: Multiple deck screens size aggregates for distribution as products or for further processing. Multiple deck screen efficiency is controlled by each deck. The multiple deck screen size usually is determined by tons per hour passing the bottom deck and the related variables associated with the equation given in Table 8.5. The efficiency of the bottom deck is most likely to vary more than that of the top two decks as the throughput in tons per hour and related variables change. Ideally, every screen should be a one deck screen sized to perform a specific task. Multiple decks are more economical since they use one drive assembly, conserve space, and reduce installation costs while making multiple separations.

Many variables and interactions between these variables regulate screening efficiency. In extreme cases, an efficiency of 90 percent is not possible regardless of the screen surface area available. Aggregates near the size of the media opening through which it should pass are most difficult to screen. Damp fine aggregates or flat and elongated aggregates also are common deterrents toward obtaining efficient aggregates separations. Bottom deck efficiency of a multi-deck screen is decreased when aggregates feed is delayed while material passes the upper decks.

Screen Bed Depth: When the bed depth exceeds four times the opening size of the screen surface, the undersize aggregates may not contact the screen before reaching the discharge end of the screen. In effect some undersize aggregates never have an opportunity to pass through the media as it is carried over on a sheet of oversize aggregates.

The screen bed depth at the discharge end should not exceed four times the size of the opening in the media. The theoretical bed depth is determined by the following formula:

$$DBD = \frac{O \times C}{5 \times T \times W} \qquad (2\text{-}13d)$$

where:

DBD = Discharge End Bed Depth (in.)
O = Oversize in short tons per hour
C = Volume of material per ton (ft^3/ton)
T = Rate of travel (fpm). Nominal 75 fpm for an inclined screen at a slope of 18° to 20° with flow rotation and usually 45 fpm for horizontal screen. Counter flow rotation on an inclined screen typically decreases the rate of travel by 20 to 25 fpm.
W = Width of screening area (ft)

Screen Selection: The theoretical screen size should utilize the bed depth calculations to determine a width that maintains the appropriate bed depth and utilizes screening area calculations to determine a length and width that provides the minimum total screening area necessary to maintain the required efficiency. *Scaling down or cutting corners in the screen size used generally results in material flow bottlenecks in screening as well as crushing.*

Most screen manufacturers have a questionnaire that prompts prospective buyers for the pertinent data required for proper screen selection. Most screen manufacturers also have guides to help in the selection and application of the various screening products available.

Options offered by screen manufacturers include spray bars, wear liners, guards, feed box, cloth, sheaves, V-belts, additional room between decks, ball tray decks, blank plate deck sections, dams, electrically heated decks, longitudinal dividers, step decks, troughs, discharge lip extensions, tension wedge fasteners, enclosures, motor bases and motors. A bid specification package should be prepared and presented to potential suppliers that reflects those options desired.

8.8 Materials Handling

The significant elements of an aggregates processing system, such as crushers and screens, are woven into a completely functional unit by the materials handling equipment; this equipment becomes an integral part of the system itself. The materials handling equipment permits the plant designer the flexibility of process equipment positioning and the selection of multiple arrangements of material storage and recovery.

Flow Control: Two basic methods are available for controlling the flow of bulk materials. One is a *gate* that gives effective control only when material size is small enough and moisture content is such that plugging or bridging does not occur. The other is a *feeder*, which is a mechanical device. A feeder provides greater accuracy of control and allows handling of material that does not readily flow through a gate or down a chute.

Feeders: Feeders provide the flexible materials handling links for controlling the flow of solids among storage, handling and processing equipment. Feeders used for metering or flow regulation are classed as volumetric or gravimetric. *Volumetric feeders* deliver a specified volume of aggregates per unit of time. Multiplication of the volumetric flow rate by the bulk density of the aggregates gives the weight rate of flow. *Gravimetric* or *weigh-feeders* provide a direct weight rate of flow regardless of the bulk density. This permits a more precise control in the feeding of solids. Feeders also are designated by their conveying element structure (apron, pan, belt, etc.) and by their flow-actuating method (vibrating, reciprocating, flight, rotary, etc.). The use of the various types of feeders in processing plant applications and the relative merits of each are described as follows:

Primary Feeders:

1. Vibrating Grizzly Feeder

The *vibrating grizzly feeder* is a popular choice in handling a large range of material sizes, such as blasted rock being fed to a primary crusher. Vibrating grizzly feeders are mechanically actuated, relatively low in cost and self-cleaning. They require a minimum of headroom, can be mounted very close to the unit being fed and require minimal cleanup of spillage.

Design: Installation is normally made in the horizontal position but can be sloped toward the crusher at angles from 5 to 10 degrees for increased handling capacity. For each 5 degree increase in slope, the capacity is increased approximately 20 percent. If feeders are sloped, the bottom of the dump hopper should also be sloped to maintain the same vertical dimension between the feeder and the hopper to minimize blockage caused by increased feeder skirt heights. Feeder skirt assemblies should be bolted to the hopper floor and constructed so that the feeder can be removed from the top of the hopper for service or replacement. The design of the feed hopper is critical to the performance of the feeder.

Sufficient dead space must be provided at the rear of the hopper to permit the impact from the truck dumping to be partially absorbed at that point resulting in less impact on the feeder. The angle of repose of material in a dump hopper can vary considerably from what is considered "normal" in the finished products. It is necessary to provide adequate height above the feeder to accommodate this phenomenon, which is often misunderstood in the design phase. The feeder should be long enough to provide sufficient room to accept a full truck load of material without overflowing uncontrollably into the crusher. It also should be long enough to provide a uniform feed rate to the crusher and permit the bed depth of material on the feeder to thin out enough to achieve reasonable efficiency of a grizzly section installed for the removal of fines prior to crushing.

When feeding a vibrating grizzly feeder with a front-end loader or excavator it is best to try to feed from the rear of the machine. This will allow the material to flow better on the vibrating pan and allow the grizzly area to remove fines. If feeding must be done from the side, try to have a pan that is at least as long as the width of the loader bucket. Otherwise, by feeding directly on the grizzly section, we render the grizzly section useless for fines removal.

2. Stepdeck Grizzly Feeder

The *stepdeck grizzly feeder* functions in the same manner as the vibrating grizzly but there is more than one level of bars for the material to pass over. When the material tumbles as it drops from one level to another, fines which may have been riding on the top of coarse particles are released from the load and allowed to fall through the bars. This type-feeder is approximately 40 percent more efficient in fines removal than the conventional vibrating feeder. Feeder skirts should be kept between ¼- and ½-inch of the side plates of the feeder to minimize carrying fines up and over the feeder sides especially with stickier feed materials. Feeder widths are normally chosen to be equal to or slightly smaller than the crusher feed opening. Wider feeders can be used, if needed, for additional capacity without increasing the crusher feed opening by using a crusher feed-box that is wider than the crusher and directs the stone off the side shelves into the crusher chamber.

3. Apron Feeder

The *apronfeeder* is a continuous steel belt unit made up of overlapping flights connected to and supported on steel chains or bars. Apron feeders are particularly suited to handling heavy, coarse or lumpy materials. Apron feeders provide positive flow and, with variable speed, provide close control of the feed rate. They normally are used for handling high tonnage of coarse material where impact loads are too severe for other types of feeders. The positive chain drive allows apron feeders to be started under full load and also permits the operator to *jog* the feeder to control large lumps feeding into a crusher. Similar to the vibrating feeder, the width normally is determined by the crusher feed width. Feeders are usually inclined upward 10 to 15 degrees to conserve height in dump hopper structure. The slope has little or no effect on the feeder capacity, but may increase the horsepower required compared to a level feeder.

Long portable apron feeders have been used successfully in providing low feed heights for portable plant crusher feed applications. If removal of fines is necessary prior to crushing, the apron feeder can discharge onto a heavy-duty fixed or vibrating grizzly feeder ahead of the crusher. In permanent operations a dribble conveyer is installed beneath the apron. The dribble conveyor collects and carries any spillage to the next conveying unit if the crusher discharge conveyor cannot be extended back under the feeder.

4. Reciprocating Plate Feeder

Reciprocating plate feeders are used in Europe as the primary receiving unit from the dump truck. Their rugged construction can withstand high impact loads and installation costs are low. Feed rate is affected by an eccentric mechanism that causes a back and forth motion of the feeder plate. The forward motion of the plate moves the load ahead and when the plate retracts, the end portion of the load is unsupported and drops off. These units feed a grizzly screen or scalper that removes the fines before crushing. Therefore, the total height and cost of the primary station generally greater is than for other types of feeders.

5. Wobbler Feeder

A *wobbler feeder* is a combined feeder and scalper. The wobbler feeder consists of elliptical steel tubes that are positioned transverse to the feed direction in alternate vertical and horizontal positions. As the tubes rotate at the same speed and in the same direction, undersized material is passed through, while the oversize is carried forward. These units are very effective in handling sticky feed materials that would build up or choke off other type feeders. The wobbler feeder minimizes clogging of the primary crusher with clay lumps or fine sticky feed.

Secondary Feeders:

1. Vibrating Pan Feeders

Vibrating pan feeders consist of a sloped trough with a flat or slightly rounded bottom having shallow sides and an open end. The drive mechanism normally is mounted below the pan but can be mounted above. Vibrating pan feeders are self-cleaning and can handle practically every type of bulk material having a wide range of particle sizes. Vibrating pan feeders require a minimum of headroom and can be mounted so that the discharge of the feeder is close to the belt or other unit being fed.

Capacity: The capacity of vibrating pan feeders is influenced by the pan width, the material depth, the inclination of the pan, the characteristics and density of the material, and the amplitude and frequency of vibration. For a given pan width, the capacity is directly related to the material weight and bed depth. Dry, free flowing material feeds at the highest rate of travel. Sticky and moist material has a tendency to create friction and results in slower travel rates. Dry free flowing material at a 5 degree down slope travels at approximately 60 fpm and changes about 12 fpm for each degree of change in slope.

Vibrating Motion: Two types of mechanisms are used to provide the vibrating motion to the pan. *Electromagnetic feeders* use high frequency, low amplitude motion to impart velocity to the feed. The feeding motion is provided by steel bars that are bent by a magnet and then released. There are no mechanical parts to wear out, but the bars are subject to moisture and dust infiltration in certain applications. Flow control is by rheostat, and is accurate and repeatable.

Electromechanical feeders have ample stroke to feed large- and small-sized materials at low angles of inclination and at high capacities. The feeding motion is provided by conversion of the rotary motion of the electric motor and the eccentric weights into an inclined stroke. Control is fairly precise and commonly imparted by a variable frequency drive.

Performance of the electromechanical-type feeder is greatly affected by the design of the feed hopper. Reductions of up to 30 percent of capacity result from deviating from proper installation guidelines. Achieving uniform flow is a function of a properly designed feed bin, hopper and gate arrangement. Materials vary greatly and the published capacity ratings may be optimistic. Therefore, each feeder installation including throat opening, slope and gate height should be verified by experience. Wear of feeder parts, though not always obvious, greatly impacts the feed rate and capacity.

2. Reciprocating Plate Feeders

Reciprocating plate feeders consist of a flat pan or plate, resting on rollers, that moves back and forth through the action of an eccentric connected to the pan. Reciprocating plate feeders can handle virtually any bulk material, but are specifically recommended for damp materials or materials containing large lumps. The design is simple and the cost is low in relation to capacity. Reciprocating plate feeders are not self-cleaning and feed in surges as the material is discharged on the return stroke of the pan. The use of reciprocating plate feeders is very limited in a modern aggregates plant.

3. Conveyor Belt Feeders

Conveyor *belt feeders* provide a positive, easily regulated, continuous method of feed control. Conveyor belt feeders can be adapted with some form of weight measurement device for precise, measurable material feeding. The belt feeder usually is constructed with flat conveyor idlers and standard conveyor components, but can be made with troughed carrying idlers. Their best application is with moderate or smaller sized materials.

Caution must be used with materials that are too sticky to discharge properly from the belt. Materials with moisture contents greater than 5 to 6 percent generally require the use of a return belt cleaner. Caution also is required in handling large pieces of aggregates with sharp edges that can damage the belt. Belt feeders completely discharge the material handled and can be fitted with adjustable feed gates.

Capacities are varied by changing the gate opening and the belt speed. Belt speeds should be limited to approximately 150 fpm. Higher belt speeds cause excessive wear and slower speeds require wider belts. Skirts and skirt rubbers should be divergent from the feed end to the discharge end to provide less friction and hence reduced power requirements. When belt feeders are placed under hoppers, the hoppers should have slotted openings in their bottom tapering about 5 to 6 percent in the direction of travel. This type of opening reduces running torque requirements about 20 percent.

4. Special Feeders

Flight feeders, table feeders, plow feeders and rotary vane feeders are used for special applications. These feeders should be discussed with the manufacturers for each specific application.

Conveyors: Belt conveyors are the arteries that keep material flowing through the typical aggregates plant. They are reliable, efficient and have relatively low operating costs. Belt conveyor selection involves three major factors: (1) capacity, (2) length and lift, and (3) material weight and size. Normal belt speeds in an aggregates plant range between 300 and 600 fpm although speeds of up to 1,000 fpm have been utilized for long, overland conveyors. The belt width of the conveyor is a compromise between the speed selected and the capacity to be handled for the particular situation. Belt width also is influenced by the material gradation and the maximum particle size.

Three roll toughing idlers are used to provide belt support and belt contour. The two outer idlers are positioned at inclinations of either 20, 35 or 45 degrees. The 35-degree trough is the most prevalent. Idler bearings require lubrication and are available either as permanently lubricated units or as greasable units which require regular attention. Both types are in common usage. The conveyor structure consists of a channel frame or truss depending upon the unsupported span length dictated by plant layout. The use of impact idlers and impact bars at transfer points can greatly reduce wear on conveyor belting. Their use is dictated primarily by the particle size of the material being handled.

Design: Belt selection is influenced by the drive horsepower and nature of the material being handled. Head and tail terminals are determined by the drive requirements and plant structural configuration. Drive pulleys generally are lagged (covered with smooth or grooved rubber) for better friction and may be provided with snub pulleys (smaller pulleys directly behind the drive pulley) to increase the degree of wrap on the drive pulley for greater power transfer capability. The Conveyor Equipment Manufacturers Association's, CEMA Handbook,[6] is an excellent reference for conveyor selection and design.

Conveyors usually are installed at inclinations up to 18 degrees, but can be increased to about a 20-degree inclination if necessary. Loading can occur on the same incline as the conveyor, but at major transfer points with coarser materials, it is preferable to load the conveyor at a 5 to 10 degrees incline and then increase the conveyor slope in a radial curve to the maximum inclination. Special belt conveyors are available for handling materials at slopes greater than 20 degrees. Ribbed belting permits slopes up to 25 degrees or more. Flexible side wall conveyors with cleats and dams normal to the belt travel are used for slopes up to 60 degrees or more.

A vertical, flexible sidewall conveyor called an elevator can be furnished. Sandwich type belting systems that contain material between an upper and lower belting unit can be used at any angle up to 90 degrees. Each of these special systems has the disadvantage of higher installation and maintenance costs, and quite often has greater nonproductive periods due to damage and difficulty of repair.

Elevators: For relatively small, free-flowing materials, *bucket elevators* provide a means to convey material vertically in a minimum of horizontal space. A variety of bucket shapes are available for the material being handled, and are supported on a chain link system or a standard rubber covered conveyor belt. A housing or total enclosure normally is part of the system and provides support for the mechanical equipment and confines material spillage.

Screw Conveyors: Fine, free-flowing materials often are handled by *screw conveyors*. Screw conveyors have pitched auger flights on a rotating shaft and are enclosed within a tubular or U-shaped housing. The flow ability, weight, abrasiveness and size of the material being handled influence the selection of the unit. Because of the many factors involved, manufacturers should be consulted for specific recommendations. Screw conveyors normally are employed in an aggregates plant for handling materials finer than the minus No. 8 sieve size. Fine material such as this is found, for example, in an air separator, baghouse or in a cement or lime feeding application for a blended product.

Chutes and Hoppers: Hopper bottom plates must be sloped to direct the material to a much smaller dimensioned discharge opening. The joint between these sloped plates is called a *valley*. The proper choice of slopes and valley angles is a requisite for avoiding segregation by aggregates size, and for achieving predictable and reliable flow in bins, chutes and hoppers. A slope that is too flat is difficult to correct. A slope that is too steep can be corrected easily to reduce excessive flow rates by the use of steps or shelves that retain materials on themselves. The proper slopes for chutes vary from 30 degrees for large rock with high initial velocity to almost 90 degrees for materials with sticky fines and no initial velocity. Modern design practices are generally the result of successful prior installations and include the following:

- Openings should be at least four times as great as the largest piece handled
- Chutes should be at least 24 inches wide to provide maintenance access
- Chutes should have easily removable covers for replacing linings or clearing plug-ups
- Chute sidewall heights should be 12 to 18 inches with open top access and should be 24 to 30 inches high if personnel access is necessary from the inside. These dimensions are suggested for practical installations and can vary up or down for special circumstances

Flowing material always should be turned by a shelf that retains the material and then placed onto the center of a belt through a divergent opening in the direction of belt travel. The free fall to the belt surface should be limited to minimize segregation.

Storage Bins: The use of storage bins in an aggregates plant includes regulating aggregates volumes during in-plant crushing, minimizing intermediate processing surges and providing large capacity product shipping storage units. Bin design must accommodate the designated purpose and be as damage-proof and maintenance-free as economically feasible. Truck loadout bins must be wide enough and high enough under the gates to provide proper clearance for the maximum size off-highway stockpile truck contemplated. The width between bin foundations must be designed to provide clearance for the loader bucket used for yard loading and/or cleanup.

Bin valley angles normally are designed to be self-cleaning, but on occasion single-size product bins are constructed with stone-box type bottoms to minimize wear. If the angle of repose of the material causes buildup on the hopper slopes, lining the hopper with low friction material, such as high density polyethylene, may eliminate the problem depending on the abrasiveness of the material.

Assisting Material Flow: Mass flow bin design parameters are readily available and provide positive discharge of material without segregation. Other methods of assisting material flow in bins or hoppers are:

- Use external vibrators if the material does not tend to compact. Vibrators should operate only when the outlet is open to flow.
- Vibrate the material inside the bin with a baffle or plate above the opening which can be externally operated by enclosed mechanisms connected to mechanical vibrators.
- Start the flow of material in the bin by using a mechanical device such as a screw or plow.
- Dry, powdery material can be fluidized with low pressure aeration pads which permit the introduction of compressed air into the material.
- Air cannons, which intermittently discharge high pressure air from receiver tanks, dislodge bridged particles of various size materials.

Stockpiling After Crushing: Finished aggregates sizes normally are stockpiled by belt conveyor or by mobile equipment. Most plants employ some combination of the two methods. While conveyors have the lowest operating costs, some mobile equipment handling usually is inevitable because of capital restraints, shipping seasonality, and imbalances between production and shipping mixes. Most operators commonly use some combination of trucks, bulldozers or front-end loaders to move aggregates once the capacities of bin or stockpile storage are exceeded. In a fractionated plant, the individual aggregates sizes are stockpiled by conveyor, and then blended into truck loadout bins or onto finished product stockpiles. Conveyors normally stockpile materials in conical piles, but the materials can be windrowed using radial or traveling stackers.

Stockpiling in Layers: The use of truck stockpiling in layers to reduce segregation quite often causes aggregates degradation. Some regulatory authorities actually require stockpiling of base material by motorized scrapers in 6 to 12-inch thick layers to minimize segregation and permit quality approval through auger sampling. This type of stockpiling is expensive and requires a large amount of space.

Contamination: Material stockpiles should be kept free of contamination from other size aggregates or foreign material. If plant conveyor stockpiles overlap due to lack of sufficient area, the intermixed material must be reprocessed in the plant or sold as non-specification material. In some plants physical divider walls are constructed between stockpiles to minimize contamination.

8.9 Loadout

The goal of a producer is to load the customer's vehicle with a quality product, in a timely manner as near the target weight as possible. Quality control should be at the top of the list of concerns in studying a plant's loading procedure. The loadout can take many forms and involve tunnels, feeders, conveyors, bins, scales, and other devices, or it can be as basic as a front-end loader loading a customer's truck from a stockpile.

Loadout Examples

One of the simplest loadout systems uses a front-end loader to move the finished product from the stockpile directly to the truck or rail car, as shown in Figure 8.12. One of the more elaborate loadout systems employs a reclaim tunnel passing beneath stockpiles of either fractionated sizes or finished products, as illustrated in Figure 8.13. A conveyor in the tunnel is fed from the stockpiles by gates or feeders that proportion the flow to meet the required specification.

Rinsing: The blended material may then be delivered to a cleaning screen which removes the fines from the product by rinsing it with water. The removed fines then require some form of processing in settling cells, sand plants or other dewatering systems before being sold as a product. A cleaning screen can be operated dry with the fines being collected in a bin for stockpiling or disposal. The collected fines can be wetted after screening and handled as slurry, as discussed above.

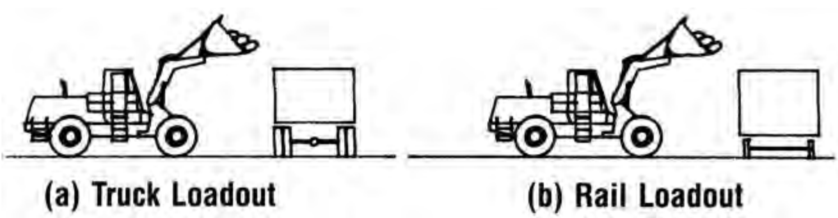


Figure 8.12 Sample truck and rail loadout.

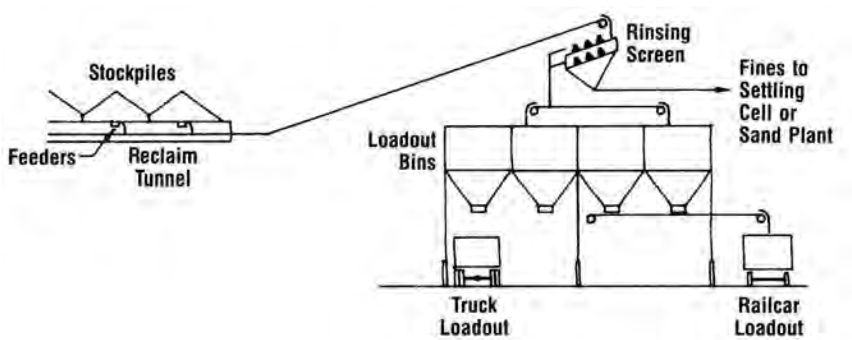


Figure 8.13 Reclaim tunnel/bin loadout.

Finished Product: The cleaned products are discharged from the screen decks by way of self-cleaning chutes into a series of finished product bins. From there the finished products are dropped through gates either directly into the customer's truck or onto a conveyor that moves the material to the truck. The trucks are then weighed and ticketed automatically at the bins or separately at a scale complex before leaving the site.

Railcar Loadout: This same type of loadout system also is used for loading railcars by locating the loading bins over a point on the plant's rail spur, or by adding a conveyor to move the products to the railcars if the loadout is remote from the spur. In other operations with these type facilities, the railcars may be loaded directly by a front end loader from a product stockpile. The railroad can provide the net weight of the cars for billing and shipping purposes. Many large producers utilize weight-in-motion rail scales at the plant to ensure that railroad weight tolerances are met. Weight-in-motion scales improve rail car turnaround and billing.

Barge or Ship Loadout: Barge or ship loadouts may involve a system similar to the one described above with a conveyor cantilevered from the dock for loading the deck barge or hopper barge, as shown in Figure 8.14. A skip loading system or a drive-on ramp also may be employed. In the skip loading arrangement a front-end loader or plant truck fills the bucket or skip of a crane. The crane lifts the skip, swings it over the deck or hold, and dumps the product. A similar arrangement also is used with a crane and clamshell bucket loading from a stockpile. The drive-on ramp employs a land-based, hinged ramp that is lowered onto the positioned barge and allows front-end loaders or plant trucks to drive onto the barge and dump the product directly on the deck.

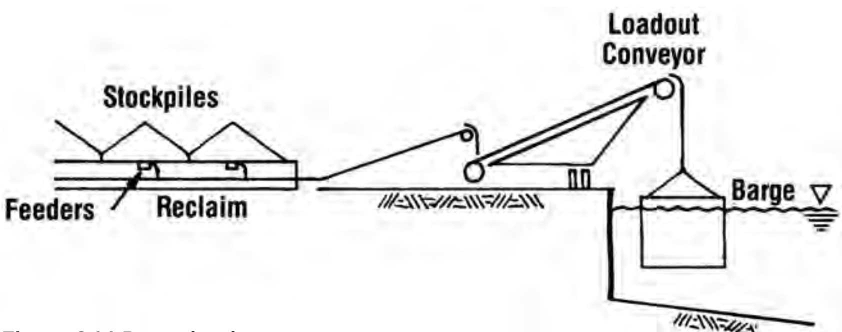


Figure 8.14 Barge loadout.

Special Considerations

Combinations and variations of these loadout systems are likely to be present in almost every plant. Loadout systems are designed to provide special considerations to the needs of the customer and the physical arrangement of the plant facilities as related to the mode of transportation used at each site.

The specifications of a material usually dictate whether a product is loaded from stockpiles or bins. For example, most clean aggregates specifications require a low percentage of minus No. 200 sieve size material. Typically, a fine rinse is a good economical method to ensure this specification is met before shipping. The clean aggregates is placed into a bin to prevent further contamination or loaded directly into the carrier's vehicle.

Flow Characteristics: The flow characteristics of a product also may determine the stockpiling methods. Riprap usually is stored in stockpiles rather than bins due to its large size and flow characteristics. Base material does not flow well through restricted openings due to the high percentage of fines and a normally high percentage of natural moisture. This combination of fines and moisture causes the material to compact. Base material is generally stockpiled on the ground and loaded with a front-end loader because of its poor flow characteristics. Similar flow problems may exist with screenings, manufactured sand and aglime. These materials may be stored in bins if special consideration is given to bin and discharge feeder design. Some state department of transportation specifications require that a controlled amount of water be added to graded aggregates to reach the optimum moisture for compaction of the base. A *pug mill* is utilized to ensure uniform mixing of the base material and the water.

Producing Several Products: A blending tunnel and fractionated stockpiles are utilized to produce a variety of products which require careful control. Fractionated sizes normally are blended to exact specification by the use of an automated system that constantly measures flow, which is crucial to maintaining quality control.

Measuring

Weight: Aggregates is weighed by various methods. For example, truck weighing includes obtaining an empty weight of the truck, loading the vehicle with the product and then obtaining a final gross weight to determine the actual weight of the product being shipped.

Rail: In a rail loading procedure, the measurement method usually is dictated by the location of the certified scales. On-site rail scales are certified by the carrier (railroad) and operate under an "origin weight agreement." If the scales are located off-site, the agreement is either termed an "average weight agreement" that includes weighing a random number of cars to determine the net weight for all cars or the agreement is to weigh each car.

Barge: With barges, the weight of the loaded product is equal to the weight of the water displaced by the vessel after loading. The freeboard of the barge is measured at each corner and the water displaced is calculated and converted to tons. If a certified weight is required, the measuring is performed by a marine surveyor.

Scales: A state agency or state-approved agency certifies scales to establish tolerances for weighing aggregates. Scale types are classified as primary or secondary and include rail, truck and conveyor belt. The *primary scales* are those that are the most accurate and are certified. Platform scales normally are used as primary scales for trucks. The most common primary scales for rail are weigh-in motion type scales. In recent years advances in electronics have resulted in increased reliability for certified belt scales. Belt scales are now a more viable cost effective alternative as a primary scale than in the past.

Secondary scales are used for internal control of the loading process. Secondary scales ensure the target weight is achieved at the loading point. Since the load is checked and verified by the primary scales before it leaves the site, the accuracy of secondary scales is not critical. Typically, secondary scales have an accuracy of ± 1 percent of the total weight.

Other Devices: Other types of devices also serve as a method of weight control. One device operates off the hydraulic pressure of a front-end loader to give its operator a weight per bucket of the product being loaded. Another device electrically controls the time that a bin gate is open and is discharging material. Another is a batching system using load cells to weigh a hopper and its contents to a predetermined weight.

Summary: The loadout must have the means to measure the discharge of materials. An efficient and exact method provides better inventory control for the producer and faster service for the carrier or customer. The trend in the industry is toward improving weighing of the loadout.

Customer Service

The competitive forces in the aggregates market require producers to decrease waiting and loading time for bulk carriers, meet tighter specifications, and maintain both consistency and accuracy in the quantities shipped. Automation of the loadout system allows the designer to provide sufficient flexibility, storage capacity and loadout rates to meet peak market demands. Computers, intercom speakers, pneumatic-tubes and card readers are all used to speed the loading and ticketing of carriers.

Illustrative Example: A truck driver drives onto a scale for an empty tare weight and orders 20 tons of a product from a traffic manager over an intercom. A plastic card encrypted with a number is given to the driver through a pneumatic tube. The driver then proceeds to the loadout and places the card into a reader. A computer reads the card's number, matches the number of the customer's order, selects and loads 20 tons of the desired products into the truck. Finally, a shipping ticket is printed at a remote location near the quarry exit.

Such automation of a loadout improves accuracy and quality, and decreases the time a truck must spend in the plant by as much as 50 percent. Other trends include better roads and traffic signals to improve the flow of traffic to and from the loadout. When highly automated loadout systems are not justified, top-off machines can be used at the scales to eliminate wasted time dumping part of a load or making a trip back to the loadout to reach the maximum legal haul weight.

8.10 Other Processing Equipment

Additional processing equipment usually is employed to handle a unique process function or special conditions. Such equipment normally becomes an integral part of the process flow. Conditions requiring such equipment include production of special products, presence of deleterious materials or abnormal fracture planes in the rock, special cleaning requirements of the products, uniform blending of materials, protection of the crusher or environmental regulations.

Rock Breaker

A rock breaker consists of a large pneumatically or hydraulically controlled boom with a high-powered, piston-actuated, reciprocating hammer mounted on a swivel base. The breaker is used to fracture oversize pieces or prevent bridging of near-size pieces in the feed to the primary crusher. Use of a rock breaker at a primary crusher can improve performance by 10 to 20 percent with proportional improvement in the loading and hauling operations. A rock breaker can also rotate, rearrange or rake the shot rock to improve the flow into the primary crusher.

Breaker Positioning: Positioning of the breaker so as to have the hammer in a vertical position when breaking the rock is important for good performance. The breaker should be positioned to accommodate jams in the hopper area outside the primary crusher cavity. Controls for the breaker usually are remotely located in the primary crusher operator's control house. Rock breakers are available in a number of boom and hammer sizes for various applications. Care should be exercised in their installation to permit the boom and hammer to be positioned for ease of maintenance and service.

Safety: Safety considerations are also one of the reasons that rock breakers are preferred over grapples or steel hooks mounted on a hoist. Utilizing the rock breaker to handle wear plates, jaw crusher liners or gyratory crusher concaves while performing maintenance in the primary area is an added benefit.

Removal of Metal

Magnets: Magnets and metal detectors are used to protect crushers from damage by tramp metal. Powerful permanent or electromagnetic magnets are positioned strategically over the aggregates flow to remove ferrous metals from the flow without stopping the conveyor belt. A magnet should be positioned as close as possible to the aggregates flow without dragging trapped metal on the moving conveyor belt. Magnets are available as plates, head pulleys and pendulum models. Each type of magnet has a preferred application. The suspended electromagnetic model typically is utilized in aggregates plants. All models are available with self-cleaning devices and may be arranged on a monorail to move off to the side to release the collected metal.

Metal Detectors: Metal detectors utilize a high frequency electromagnetic field to detect the presence of metallic particles. The detectors are mounted so the material on the conveyor belt passes through the electromagnetic field. Once the metal is detected, the belt is stopped and the metal removed. A spot of paint may be sprayed automatically on the material at the point of detection to permit rapid location and removal of the foreign object. Otherwise, the belt coasts a predetermined distance where the object is sought out and removed.

The magnet and the metal detector perform similar functions and quite often are used together to minimize the amount of time the belt must be stopped. The magnet pulls the ferrous metals from the material flow without stopping the belt. The metal detector placed downflow of the magnet stops the belt so any remaining metals can be removed.

Use of a magnet and stopping of the belt both can be eliminated by automating a diverter following a metal detector to bypass the small section of the metal-contaminated material from the process flow.

Pugmills

A *pugmill* consists of twin, counter-rotating shafts with interlocking mixing paddles inside a metal hopper. A pugmill should be used when a specific moisture content and a uniform blend of base material is required. A single or multiple aggregates source can be fed to the pugmill to meet the gradation control and specification requirements. Controlled moisture content is obtained by utilizing carefully placed water sprays during mixing. In addition, cement, lime, calcium chloride or even bitumen products can be evenly fed into the pugmill from bulk storage in specifically proportioned quantities to produce stabilized aggregates bases. A pugmill provides the contractor with a product that can be readily compacted with reliable quality assurance.

Washing Equipment

Most coarse aggregates products can be adequately rinsed over a vibrating inclined screen utilizing high pressure spray nozzles. One to three gallons of water per minute per ton per hour of aggregates usually provides sufficient rinsing. Manufacturers, however, recommend three to five gallons per minute per ton per hour. Four important factors which minimize the required rate of water are: (1) properly designed and located high-pressure spray nozzles, (2) regulated material bed depths on the screen, (3) dry removal of fine material before rinsing and (4) pre-wetting material before it is placed on the screen.

Screw Washer: When rinsing alone does not sufficiently clean the aggregates, a coarse-material screw washer can be used to remove clay, dirt and crusher dust particles. If the specific gravity of the deleterious material is very near that of the aggregates, a heavy media solution can be used to provide a more exact split of the two materials. The coarse material screw washer also acts as a gravity flow device and floats off vegetation and lighter, low-quality aggregates. In coarse material screw washers, paddles in a pool of water churn the aggregates to provide a scouring effect. Screws then dewater the washed aggregates for stockpiling.

Log Washer: To be properly cleaned, aggregates containing tough plastic clays, cemented aggregates and certain conglomerates need the rigorous agitation of a *log washer*. In a *log washer box*, interlocking paddles on twin parallel shafts agitate the aggregates as it is pushed along the inclined box floor to the discharge chute. Waste water and suspended clays in the lower pool area of the box are discharged through openings at the water level in the feed end of the unit. Discharged semi-cleaned aggregates normally require rinsing to remove any adhering clay solutions prior to use as clean material. For best performance, the gradation of the aggregates in a log washer should be limited to a top-to-bottom size ratio of two-to-one with a minimum of fines to ensure maximum particle interaction.

Rotary Scrubber: A *rotary scrubber* also is capable of high-capacity, heavy-duty washing. The scrubber is effective in removing high contents of soluble waste such as dirt, soft rock and light clay from the good aggregates. Material is fed into the horizontal, slightly inclined rotating scrubber drum normally equipped with lifting angles, where it is tumbled upon itself as it progresses to the discharge end. The aggregates discharges over a dewatering screen for further handling while the waste and fines are passed through the screen for further handling or disposal.

Wet Classifiers

Often the need arises to classify solid aggregates contained in slurry. When the slurry is discharged into a *classifying tank*, the excess water in the raw feed is scalped off. The slurry containing the solids is fed into a tank pool with a regulated amount of water where it is evenly sorted into specific sizes by the water flowing over the length of the tank. The coarser solids settle out at the feed end of the tank; the finer solids at the discharge end. Valves at various intervals in the tank floor blend the graded solids into usable products and waste any excess sizes. The products are flumed to a fine material screw washer where the material is dewatered utilizing an inclined screw. The screw overflow typically requires 50 to 100 gallons per minute per ton per hour of solids in the overflow.

Hydrocyclones employ centrifugal force in a conical-shaped structure to classify and de-water aggregates solids from a slurry. Hydrocyclones can recover minus No. 150 sieve size solids that are ordinarily lost as waste in the overflow of fine material screw washers. Simplicity of installation and maintenance are advantages of the hydrocyclone.

Pumps

The aggregates plant may require water for stone rinsing and washing, cleanup or dust suppression. *Vertical turbine* or *centrifugal pumps* supply the freshwater requirements for plant operations as well as pit dewatering. Wear resistant centrifugal pumps are used to transport the process slurry to retention areas for settling and reuse. Closed circuit water requirements for a typical one million ton per year aggregates plant with 65 percent clean stone are approximately two million gallons. The closed circuit requires a source for makeup water containing a minimum of four million gallons.

Grinding Mills

Grinding mills are used to produce a wide range of fines varying from manufactured sand to super fines used in specialty products. The grinding media are either rods or balls; thus the name *rod* or *ball mills*.

The grinding process is either wet or dry. The rod mill is limited to producing coarser fines fraction products such as manufactured sand. Due to economics, most aggregates plant ball mills use a dry process and air classifiers for the final separation of finer specialty products. Roller mills and vibrating mills are used to produce fillers and special industrial products.

8.11 Electrical Systems and Energy Management

The increasing costs and sophistication of the electrical and control systems require a high degree of involvement by professionals with skills in this area during the design, operation and maintenance of an aggregates plant. Electrical systems account for as high as 25 percent of the initial capital construction cost. Also 10 to 15 percent of plants operating costs are spent on energy.

Electrical engineers traditionally design the power distribution system for an aggregates plant including selecting the electrical equipment and supervising electrical construction. The electrical, processing and project engineers carefully should coordinate the development of all aspects of the electrical control system. *Automation should be integrated into the initial design stages of the plant.*

Design Considerations

Monitoring and control components must be resistant to dust and moisture, and must be vibration tolerant. Programmable controllers typically are used for monitoring and controlling processes and can be interfaced with controls that automatically shut down predetermined processing units. Electrical equipment should be located to facilitate maintenance and cleanup.

The maximum size motors for across the line starting should be approved by the utility. Motor horsepower should be specified to actual starting and load requirements, and include a reasonable operating safety factor. The operating system power factor should be maintained above 90 percent to avoid energy losses and billing penalties. The electrical design of the plant system must be in accordance with the latest edition of the National Electrical Code[7], local state and municipal codes, National Electrical Safety Code, Occupational Safety and Health Act, Mine Safety and Health Act, and National Fire Codes.

Energy Management

The most efficient use of electrical energy is achieved by operating the processing plant at optimum performance. The demand (expressed in kilowatts), usage (expressed in kilowatt hours) and the rate structure from the utility are the three most significant factors in most economic evaluations concerning energy management. Electrical demand can be limited by scheduling multiple shift operations, utilizing intermediate surge piles to alternate operating various independent processing circuits and operating the pit pumps during off peak hours. A checklist for electrical systems and energy management is given in Table 8.6. Effective energy management can be automated and yield savings of 10 to 25 percent in the operating power cost.

Table 8.6 Checklist for Electrical Systems and Energy Management

1. Include electrical engineers, consultants, etc., from the beginning of any project involving electrical work.
2. Make energy management an integral part of any electrical project, especially those involving automation. Large potential savings are available through demand control. Operating segments of the plant offers the greatest potential for demand control and significant electrical cost reduction.
3. Consult the electric utility in advance of any project to determine rate riders, discounts, off-peak rates, etc., and other ways to save money.
4. Obtain necessary electrical permits in the early permitting stages of all projects.
5. Give pump design and application a high priority. In some cases, pumps contribute a large portion of the demand load.
6. Use proper motor size for the applied load. If future projects require an increase in capacity and motor size, design the system components for this future load including sizing reducers and electrical transformers, breakers, starters, conduit and wiring. Increase motor size as needed in the future.
7. Place proper emphasis on hiring and training of quality electrical personnel to fully realize the savings and benefits of a good electrical maintenance program.
8. Keep electrical wiring organized, out of the way and damage free.
9. Strive for uniformity in motors, switches, etc.

8.12 Safety Considerations

Introduction

Safety is of prime importance in an industrial environment such as an aggregates plant that consists of operating machinery working in varying environmental conditions. About 15 percent of all accidents are caused by unsafe mechanical or physical conditions. The other 85 percent result from absentmindedness, negligence or ignorance of risk that are beyond the scope of the plant designer. For each accident, 100 incidents occur that are near-misses. The plant designer has an obligation to provide a work place that minimizes the possibility of situations that lead to near-misses and accidents.

Checklists should be prepared to make sure all safety-related items are considered. A safety engineer should review the final machinery and structural plans, and ensure compliance with the appropriate MSHA regulations.

Comments on Specific Equipment

Some general comments concerning safety aspects for specific equipment and machinery are given in this section. For detailed safety requirements refer to the applicable codes and regulations.

Crushing Machinery:

1. Ample workroom should be provided around the unit for personnel movement and the use of tools.
2. Platforms should be provided so service and/or observation areas can be accessed without climbing on the machinery. Safe access should be provided to all locations where adjustment, service or sampling is required. All platforms should be strong enough to withstand falling

rock or buildup of materials. Where possible, lifting devices should be installed to aid in the replacement of liners and other wear parts.
3. Crushing feed chambers should be shielded to prevent fly-rock injury or accumulation of material on platforms.
4. Adjustment tools or hydraulic hoses should be racked or kept off the floor area to prevent tripping of personnel.
5. Properly designed mechanical devices should be provided to permit crusher service and maintenance to be performed without using unsafe procedures.
6. Engineered and prefabricated guards for moving parts of machinery should be provided. They should be easily removable and replaceable.

Screening Machinery:

1. Walkways alongside and parallel to the screen slope should be provided to permit access to the clamping bar bolts and screen frame connections. These walkways can be continuous sloped ramps or stairs with risers and long tread sections.
2. Ample clearance should be provided to permit safe access around the drive unit.
3. Drive guards should be provided that permit easy access for changing drive parts. These guards also should protect the drive system from loose rock that can damage the drive mechanism.
4. Safe access to the screen decks is very important and accomplished by rolling away the discharge chute at the end of the screen or by use of hinged gates in the chute work. The rollaway chute is considered an overall safer procedure than hinged gates.

Conveyors:

1. Walkways should be provided for service, inspection and product sampling. Expanded metal, grating or special nonskid products should be used on inclined walkways.
2. Short walkways are recommended at vertical gravity take-ups and at the terminals on both sides of conveyors with single walkways. Crossover bridges or walk-arounds are required for access.
3. Pinch points along the conveyor need to be protected to prevent inadvertent access to these hazardous areas.
4. Pull cords or inside handrails should be provided at the idler height on conveyors with walkways and/or personnel access that are not visible to the plant operator. This is a MSHA regulation.
5. Cages or guards on return idlers must be provided if the area is accessible to personnel. Consult the MSHA regulations for specific requirements.
6. If conveyor inclination or material size could result in the rollback of materials, buffers need to be provided at sufficient points to eliminate the hazard of falling rock.
7. Machinery guards must be lightweight, rugged, and easily removed and replaced for inspection and repair.
8. Vertical gravity take-up weights must be guarded at grade to prevent personnel access under the weights. Fencing, chain, cable or other procedures to suit the situation can be used. The gravity take-up weight should be installed at the lowest practical elevation to limit the drop height in case of belt breakage.

Stairways:

1. All working levels of a plant building need stairway access if at all possible.
2. Stairs should have a minimum width of 30 inches and be constructed at a slope of 30 to 35 degrees, with a constant riser height.
3. Landings should be provided at appropriate intervals.

Ladders:

1. Stairs are always preferable to ladders. If a stair installation is impractical, ship-type ladders inclined at 60 degrees should be considered. Vertical ladders should be used only as the last resort.
2. Where ladders are required, rungs should be spaced at 9 to 12 inches apart, and be at least 18 inches wide. Safety cages are required for ladders over 7 feet and should be designed following all applicable regulations.

Platforms:

1. Handrails at 42 inches with mid-rails are required unless an area is enclosed with mesh or plate. Materials should be made from adequate structural shapes such as pipe and square or rectangular tubing. Angle or solid rod also can be used but are not efficient structural shapes. Handrail posts are normally spaced on 8-foot centers or as needed by the particular application.
2. Toe boards around the edge of the floors should be a minimum of 4 inches high and may be placed approximately 1 inch above the flooring to facilitate clearing and reduction of buildup of materials on the flooring.
3. Flooring can be steel checkered plate, expanded metal grating, or a variety of other prefabricated, nonskid flooring products. Wood, rubber belting or used screen cloth are not recommended. Open-type flooring allows material to drop to lower levels or to the ground to facilitate cleanup.
4. Openings in the floor should be guarded by handrails and toe boards, and the access openings should be protected.

Material Storage:

1. Open hoppers or bins that are in the plant working area should be covered or protected by proper handrails and toe boards.
2. When internal bin access is required, ladders should be provided as well as life belts or harness suspension facilities.

Maintenance Equipment:

1. Hoists should be installed wherever major heavy components need to be handled that cannot be reached by a crane. Electric hoists should be provided in buildings with multiple floors to permit handling of screen cloth, machinery parts, etc.
2. Equipment and parts storage should be provided in the buildings at or near the point of use to facilitate maintenance installation. Storage areas should be designed to be safe, accessible, and easily cleaned and maintained.
3. New and remodeled structures should be provided with electrical and welding outlets at each floor level to eliminate time and danger in handling leads from portable welders at ground level.

4. Water line riser pipe should be installed to floor levels of the structure that can more readily be cleaned by water flushing than by shoveling or sweeping. Hoses and hose storage racks need to be provided at each floor and should be of a size that easily can be handled by one person.

Electrical Safety Recommendations:

The National Electrical Code[7] should be used as a design guide, together with any local or other codes that apply. Several areas that deserve special attention are as follows:

1. Underground power cables should be installed at least 4 feet below the surface with high visibility warning tape 1 foot above the shallowest conductor. In areas where machinery activity is anticipated, PVC conduit encased in concrete provides greater protection of personnel. PVC conduit encased in concrete should be used for circuits over 600v. Bright colored dye may be added to the concrete to enhance visibility during subsequent excavation.
2. Overhead power lines should be installed at least 20 feet above general pedestrian and light truck traffic and 35 feet above established roadways. Special attention should be given where crane work is probable such as around settling ponds, crusher foundations and screen towers.
3. Overhead power lines should not be placed above or around stockpiles. Stockpiles tend to increase in height up to the lines and can constitute dangerous operating conditions for loaders and trucks.
4. Always use wire that is insulated properly for its intended application. Underground wire even in conduit must be waterproof. Exposed wiring should be both waterproof and sunlight resistant.
5. Motors should be controlled by manual or magnetic starters. Fused switches are not safe in this application.
6. Power panels with exposed current carrying components should be replaced with enclosed equipment that meets current code specifications.
7. The exits from all electrical equipment rooms should be kept clean.
8. All metallic electrical enclosures should be connected to each other with copper conductors throughout the entire plant.
9. All ground level electrical equipment should be enclosed by a fence or building and locked so only authorized personnel have access. These areas should not be used for any other purpose.
10. Fuses should not be placed in electrical circuits that are larger in capacity than the design size. Repair the electrical problem to permit equipment operation using the correct fuse size.

Other Important Safety Considerations:

1. Clearances are one of the most overlooked safety areas in the design of a new plant. Floor-to-ceiling heights should be adequate for personnel and equipment; and structural bracing should be designed to consider door opening sizes and work platform locations around equipment. A remote stair tower can be located outside the equipment structure that facilitates equipment access and simplifies the design of the structure.

2. Safety also can be enhanced by the use of readily available electrical and mechanical equipment such as belt alignment switches, chute level sensing devices and sensors which detect excessive equipment vibration, etc. These sensors will alert the operator of possible problems and will shut down a piece of equipment if the condition is not corrected. Keep material spillage controlled to eliminate loose material on walkways and stairs, repair oil leaks immediately and clean up any spillage. Repair (do not patch) leaks and remove scrap materials from repair jobs to proper disposal areas.
3. Good illumination is essential for safe working conditions by providing natural or artificial lighting of sufficient intensity.
4. Baskets for lifting personnel should be designed for the specific application and be approved by the plant safety engineer.
5. Trucks with special buckets for lifting personnel should be used to service elevated areas instead of using ladders or standing in front-end loader buckets.

8.13 Environmental Considerations

Plant environmental factors including dust, noise and water must be addressed in the design stage to anticipate problems and provide means of correction that satisfy the applicable regulations. Plant design must include a thorough review by the operating and environmental personnel, and possibly by special consultants, to ensure an acceptable environmental control system.

Dust Control in the Plant Area

Wet and Dry Suppression: All sources of airborne dust in the processing plant must be reviewed for control requirements. The control method may include wet suppression systems, dry collection systems or a combination of both. *Wet suppression systems* use treated or untreated water applied to the aggregates in a spray or fog condition to wet down the airborne particles of fine dust and cause them to settle back into the process stream.

Dry collection systems use hoods and enclosures to contain the dust. The air and dust is transported in ductwork to a central collection point where the dust is collected in a baghouse. The dust is disposed of separately, sold as a product or put back into the process stream. Conveyor feeds and discharges, crusher feeds and discharges, screen feeds and discharges and open chute work provide the greatest sources for dust generation. These sources of dust must be evaluated in detail to determine the most appropriate dust control design. The types of dust control enclosures and methods of sealing them are important considerations. *Vacuum ducts* are connected to the enclosures to create an airflow into the area and then into the ductwork.

Open Stockpiles: Open stockpiles formed by conveyors or trucks are sources of airborne dust. Airborne dust can be minimized by discharging pre-wetted feed. The elevated oscillating sprinkler is one of the most effective long-term control systems. Elevated oscillating sprinklers can be engineered to cover the total yard area with pre-programmed operation to maintain proper moisture limits.

Dust Generated by Traffic: Dust generated by vehicle traffic in and around the plant is one of the prime sources of airborne dust. This dust usually is controlled by water trucks that periodically spray water and/or chemicals on the roadways. Paving of major traffic areas is an effective method of reducing the amount of dust. Paved roads, however, require cleaning by water flushing or mechanical sweeping. Pipelines and oscillating sprinkler heads can be installed alongside major roadways (paved or unpaved) to permit automatic, programmed watering as conditions dictate.

Washing Down Trucks: Wash-down systems are sometimes required by regulatory authorities to remove any loose materials accumulated on the delivery truck wheels or under-body prior to the truck leaving the property. Some regulations require the sprinkling or wet-down of loaded trucks prior to leaving the plant to reduce airborne dust from the load caused by high travel speeds on the highway. Regulatory authorities often require that all loads be tarped or covered for travel on the highway.

Use of Surfactants: The use of chemical additives, called *surfactants*, in the dust control water system should be considered. These chemicals reduce the surface tension of the water and eliminate the tendency of dust particles adhering to the droplets of untreated water. This provides more thorough dust control, uses less water and minimizes the blinding effect on fine screening surfaces. Maintenance of dust control systems is critical to the effectiveness of the emissions control.

Dry Dust Control: To meet mandated requirements, some plants in highly populated or environmentally sensitive areas may have to provide totally or partially *dry dust control systems* such as baghouses, equipment enclosures, and air collection and handling systems. A properly designed dry collection system emphasizes controlled air flow to confine most of the airborne dust rather than collect it. Some individual air collection package units are now available which permit mechanical dust collection and handling at singular locations. *If these dry dust control systems continue to satisfy the codes, they offer the best available technology for controlling dust.*

Building Enclosures: Building enclosures for screening plants confine dust within the area, but limit equipment visibility, reduce maintenance accessibility, and subject the plant personnel to high levels of dust exposure that require personal protective equipment.

Noise Control

In an aggregates processing plant, the noise generated by heavy equipment operations and by the movement of material through the processing plant is minimized by the following techniques:

- Low profile process systems can be used where the mechanical equipment is closer to the ground and noise travel can be buffered by berms or trees. This concept is discussed further in Chapter 5.
- Handling materials with rock-on-rock interfaces for transfers can reduce noise appreciably compared to rock on steel interfaces. Stone boxes at transfer points reduce noise as well as maintenance costs.
- Rubber or polyurethane products for screen surfaces, chute liners, stockpile truck liners, etc. minimize noise in materials handling.
- Building enclosures minimize machinery noise but must normally be insulated to provide effective noise reduction.
- Non-audible backup alarms on selective pieces of equipment reduce the problem of disturbances caused by the normal audible backup alarms.

Process Water Control

One of the most challenging parts of a plant design effort is the handling of the waste water and its products that are discharged from the processing streams of a normal plant operation. If the plant process operates dry, some of the final clean stone products may require rinsing to meet specifications. In addition, the demand for manufactured sand from stone screenings is increasing and this generally requires the use of water separation of the excess fine material. Handling of the process water is a relatively simple task. The recovery and disposal of the fines are difficult and can be handled in one of the following ways:

Closed Circuit Settling Ponds: The traditional method for the disposal of fines is to discharge the waste into *closed circuit settling ponds* for decantation. The use of this approach is diminishing. A number of ponds must be constructed and large areas are required. The material in the ponds must be excavated regularly. The fines removed are hauled to a disposal area which is an expensive and difficult process. The most cost-effective way of disposal is the construction of permanent disposal areas where fines are pumped directly from the cleaning process. However, these types of impoundments must normally be approved by state authorities and the water return system monitored constantly.

Concrete Containment Cells: The use of above-ground *concrete containment cells* provides a method of settling out the coarser fractions of the wash water that permits access with front end loaders after water decantation. The use of containment cells enables the material to be handled by truck in a more cost-effective way. The overflow water from these basins is still collected in ponds to undergo final sedimentation. The time between clean-out periods for these type ponds, however, is greatly extended.

Clarifiers: Clarifiers are a means of eliminating the use of ponds and their associated cleaning expenses. *A plate clarifier* is a system of closely spaced inclined plates at a one-to-one slope that provides a multiple passage for water and fines. A plate clarifier permits an installation in one-tenth the space required for circular clarifiers. In a *circular clarifier*, sometimes called a thickener, settled particles are moved to the tank center by radial rakes for discharge. These units are constructed of steel or concrete and normally have a large diameter (80 to 150 feet) to provide a quiet pool for particle settling. The rake clarifier is a rectangular tank with a slow-moving drag flight conveyor that removes settled solids up and over a discharge ramp onto a dewatering pad or basin. When proper flocculents are added, this unit has a discharge with a moisture level that enables loader handling fairly quickly. Belt presses and vacuum filter systems are available to remove residual moisture from the effluent. However, these systems are quite expensive and not likely to receive wide acceptance unless the product can be sold for commercial use.

Makeup Water: Most plant process water systems are essentially *closed circuit systems*, with no water discharge leaving the property. Makeup water is provided by ground water runoff and quarry seepage. Water wells, where permitted, are also part of the normal plant water system, both for makeup and sanitary purposes.

Plant Drainage Systems

Providing for plant drainage and storm water control is essential in the design phase due to the stringent controls being imposed by government authorities on plant water discharges. The plant drainage design must accommodate process plant cleanup water from the plant maintenance systems, cooling water from the crushing systems, building drainage and runoff from yard watering systems. Drainage structure levels must be established that permit proper water flows in and around the buildings and stockpiles. Water courses, such as ditches and storm sewers, must be provided that do not interfere with plant operating or maintenance procedures. Most quarry operating permits require sufficient water storage capacity to contain the flow from unusually severe rainfall conditions and sufficient time for settlement of suspended solids. This water is stored in ponds and released to the normal water courses when the water quality requirements of the plant discharge permits are satisfied.

Flocculents

The use of flocculents in waste water handling is becoming more prevalent. *Flocculents* cause the rapid settling of coagulated fines and enable the immediate reuse of the clean water in the plant process. The more rapid recycling of the waste water reduces the volume of water handled and simplifies the required plant makeup water systems. The use of flocculents does not, however, provide a solution for the handling of the effluent and suspended fines as previously discussed.

8.14 Plant Design

Plant design begins by compiling all known processing parameters which were considered in Section 8.2 and follows the development of project methods as outlined in Section 8.3.

The goal of the plant designer is to select equipment that meets processing parameters and arrange that equipment into a system which is balanced to produce finished sizes in the proportions required. Considering the complexity of this goal and parameters involved, it is not surprising that processing plants differ widely from location to location. The variety of challenging situations leads to some ingenious solutions for the design of processing plants.

The following subsections deal with the development of a basic plant flow sheet and some plant design alternatives that may improve production, product yield and gradation uniformity.

Basic Plant Flow Sheets: An Illustrative Example

A processing plant flow sheet is a model that attempts to predict plant performance. The flow sheet forms the basis for the selection of components to meet project goals. The techniques of flow sheet development are common to all processing plants, regardless of size.

The following flow sheet example is for an in-line (*sequential*) flow process having three crushing stages. The objective is to produce 500 tph of minus 1-inch size product from a biotite granite quarry. The developed flow sheet shown in Figure 8.15 provides the necessary tonnage information for equipment size analysis. The quantitative values shown have been developed from manufacturers' charts and tables, or from the designer's experience based on test data for similar material processed through similar equipment.

Primary Crusher Selection: The first step in flow sheet preparation is to determine the required size and type of the primary crusher. The compressive strength and abrasiveness of granite suggest the use of compression-type machines throughout this plant. Five hundred tons per hour is within the range of a jaw-type primary crusher fed with a vibrating grizzly feeder to remove fines already small enough to bypass the primary crusher.

Figure 8.16 shows an analysis of particle size of quarry run material for several different types of stone. Biotic granite, the raw material for this example, is shown on curves 3 and 4 of Figure 8.16. Note that approximately 35 percent of the stone passes a 6-inch opening and is small enough to bypass the primary crusher. Feeder grizzlies are usually short, heavily loaded and therefore fairly inefficient. For this reason, assume that only 20 percent of the possible 35 percent quarry run material (100 tph) bypasses the primary jaw crusher through the feeder grizzly. The remaining 400 tph must be processed through the jaw crusher.

Secondary Crusher Selection: The jaw crusher product and the bypass product are combined on one conveyor and sent to the secondary screening and crushing station. A combined gradation of these two flows is determined to evaluate how the material splits at the secondary screen shown in Figure 8.17. Since a vibrating screen is never 100 percent efficient, adjustments are made to the amount of stone coming from each deck of the screen to reflect screen inefficiency. The secondary crusher and screen sizes are determined from these quantities.

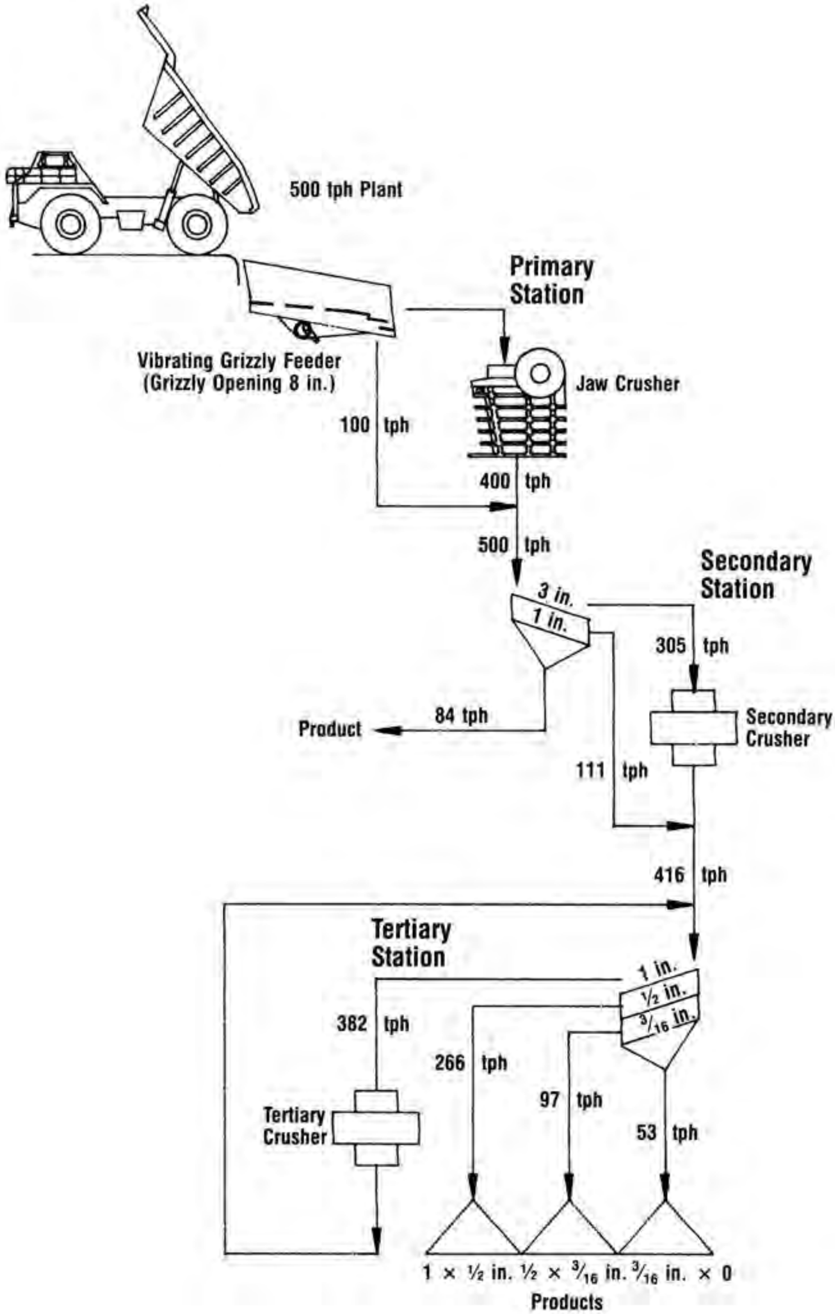


Figure 8.15 Typical flow path of a 500 tph plant: surcharges are not shown.

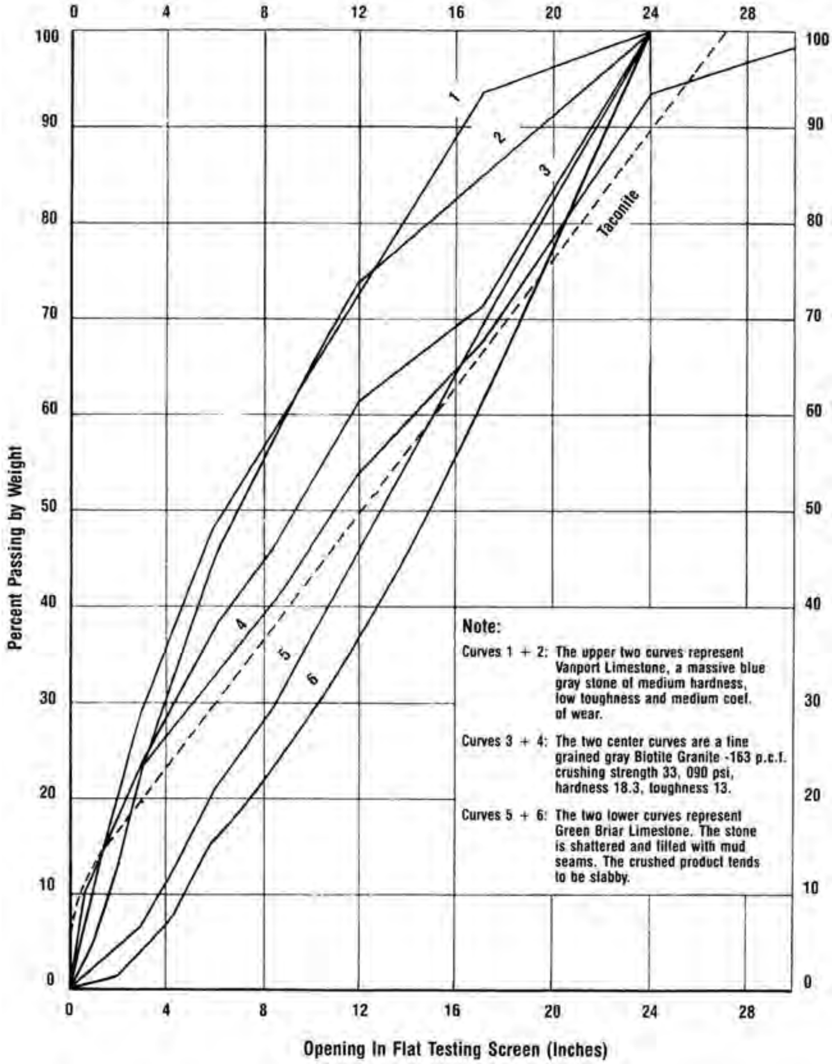


Figure 8.16 Screen analysts of quarry run material from several different quarries.

Cone Crusher Product: The crushing action of a cone crusher is created by the transverse motion of the crushing head (or mantle) creating a crushing stroke sometimes called an eccentric throw or head displacement. The aggregates flowing downward in the crushing chamber is crushed against the stationary bowl liner. The smallest opening between the head and the bowl liner is called the close-side setting. A fully fed cone crusher reduces a normal feed to a product which is nearly smaller than twice the close side setting measurement of the crusher. For example, if the desired product from the secondary crusher is minus 3 inches, a crusher capable of handling the required tonnage while operating at a 1.5-inch close-side setting is required. One manufacturer's capacity charts show that a 4.25-foot cone crusher meets these requirements with a capacity rating of 325 tph.

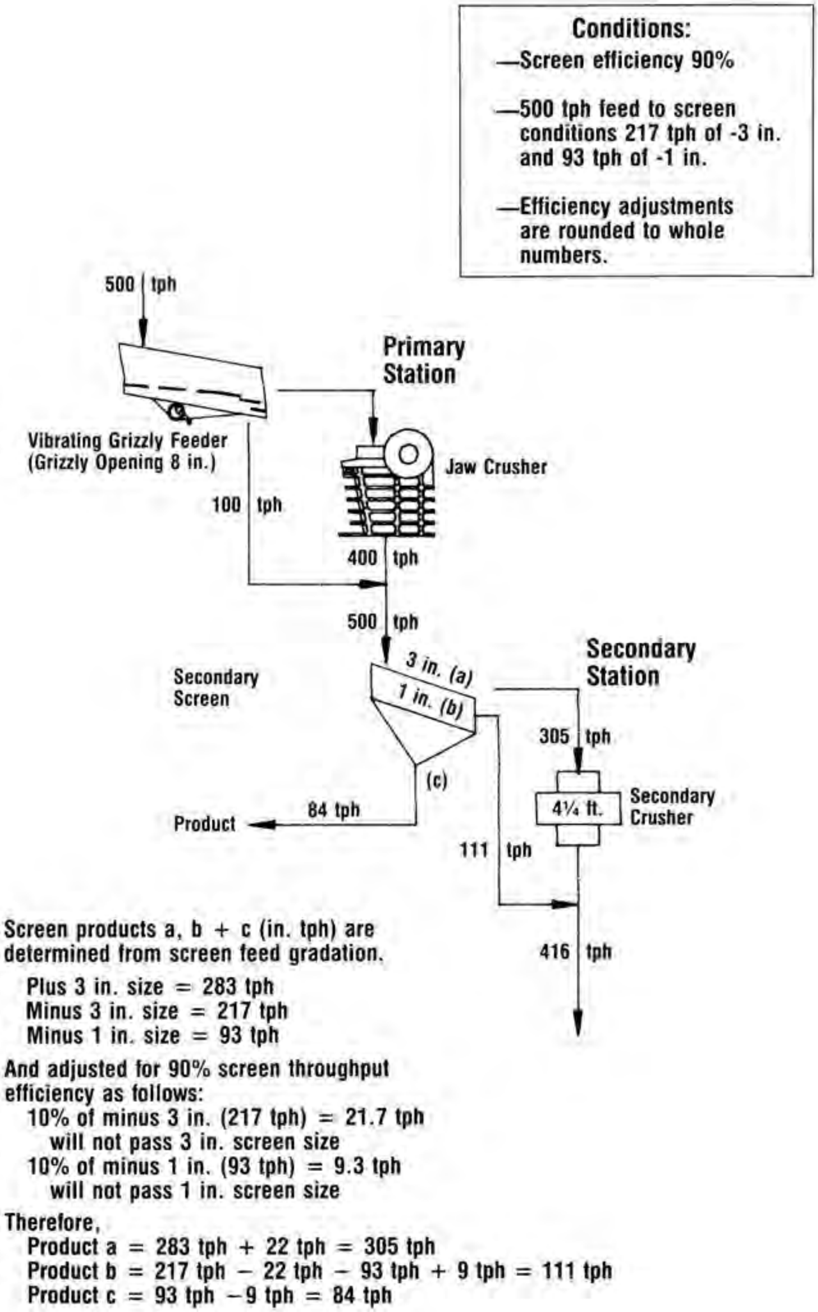


Figure 8.17 Primary and Secondary flow path: 500 tph capacity.

Finer Product: If a finer product is required at this stage, a larger crusher would be selected capable of meeting capacity requirements at a smaller close-side setting. For example, a 5.5-foot cone crusher fitted with a medium crushing chamber has the same capacity at a 1-inch close-side setting as does the 4.25-foot size at 1.5-inch close-side setting. Product from the larger crusher would be expected to be nearly all minus 2-inch size particles. Smaller crusher settings, with the same size feed, results in a higher crusher reduction ratio. Secondary crushers must accept large size stone coming from the primary crusher.

Crusher Efficiency: Small secondary crusher settings result in higher power demand, making these crushers difficult to control. Operators are likely to reduce feed rates or increase the discharge setting to avoid stalling the crusher under these conditions. A smaller machine operating with the larger setting is often the better choice for this stage, passing more of the crushing duty onto the finish stage or stages.

Example Summary: At the secondary stage, 84 tph of minus 1-inch product is removed from the circuit, 111 tph of 3-inch by 1-inch stone bypasses the secondary crusher, and 305 tph is processed in open circuit through the secondary crusher. The size gradation of the combined 416 tph of stone processed is determined from crusher manufacturers' charts or performance data from similar operations. A typical crusher performance chart is shown in Table 8.7.

Tertiary Crushing: The tertiary crusher flow path shown in Figure 8.15 is a closed circuit system. Stone coming from the secondary crushing station that does not pass through the 1-inch top deck opening of the tertiary screen is fed into the tertiary crusher. The tertiary crusher's product recycles back to the same screen where any material remaining larger than 1 inch is fed again into the tertiary crusher. A closed circuit affects the size of the tertiary crusher and screen surface area required, since the screen and crusher must handle the initial load plus the circulating material (load).

Circulating Load: The circulating load builds as a geometric progression based on screen efficiency and the percentage of rock reduced to product size by the closed circuit crusher. Table 8.8 provides one way to calculate circulating load. For the flow sheet being considered, it is assumed that screen efficiency is 90 percent and that the crusher reduces 85 percent of its throughput to smaller than 1 inch. Entering Table 8.8 using these factors, a circulating load factor (R) of 20 percent is found. The circulating load factor is multiplied by the original feed to the tertiary crusher and then added to the amount of stone in process. The data in Table 8.8 demonstrate how improper selection or operation of equipment result in very large circulating loads.

After an initial flow sheet is made and equipment sizes are selected, the flow paths, screen opening sizes, crusher settings, etc. are re-analyzed to balance circuits for the most productive effort with available equipment sizes.

Table 8.7 Standard Cone Crusher Capacity[9]

Open Circuit—Capacities in short tons per hour passing through at indicated discharge setting "A"

Size	Type of Cavity	Recommended Minimum Discharge Setting "A" (in.)	Feed Opening With Min. Recommended Discharge Setting "A" (in.) "B" Close Side	"B" Open Side	3/8 in.	1/2 in.	5/8 in.	3/4 in.	7/8 in.	1 in.	1 1/4 in.	1 1/2 in.	2 in.	2 1/2 in.
3 ft	Fine	3/8	3 5/16	4 1/16	50	65	80	90	100					
	Coarse	1/2	6 3/8	7		65	80	100	110	130	150	180		
	Extra Coarse	1	6 1/2	7 1/8						130	150	180		
4 ft	Fine	3/8	5	5 1/4	70	100	120	140	155	170	185			
	Medium	1/2	6 1/8	6 1/4		110	130	150	160	180	200	220		
	Coarse	3/4	7 1/8	7 5/8				155	170	200	220	270	340	
	Extra Coarse	1	9 1/4	10						210	230	280	350	
4 1/4 ft	Fine	1/2	4 3/8	5 3/8		120	140	160	170	180	200			
	Medium	5/8	7 1/2	8 1/4			145	175	190	220	250	280		
	Coarse	3/4	8 5/8	9 5/8				190	215	240	275	325	385	
								Refer to Example in text						
	Extra Coarse	1	9 1/2	10 3/8						260	300	335	395	
5 1/2 ft	Fine	5/8	7 1/2	8 3/8			200	225	250	285	325	360		
	Medium	7/8	8 1/2	8 5/8					285	320	370	420	460	
	Coarse	1	9 5/8	10 3/4						330	390	460	500	700
	Extra Coarse	1 1/2	13 1/4	14 1/4								475	525	750
7 ft Heavy Duty	Fine	3/4	10 1/8	11 1/8				420	450	550	680	800		
	Medium	1	12 1/8	13 3/8						670	800	890	1100	
	Coarse	1 1/4	13 3/8	14 3/4							870	930	1200	1400
	Extra Coarse	1 1/2	16 3/4	18 1/8								970	1300	1500

Table 8.7 Standard Cone Crusher Capacity[9] (continued)

Close Circuit—Capacities in short tons per hour passing based on closed circuit operation

		Effective square opening of close circuit screen																			
		3/8 in.		1/2 in.		5/8 in.		3/4 in.		7/8 in.		1 in.		1 1/4 in.		1 1/2 in.		2 in.		2 1/2 in.	
		Recommended close side settings for close circuit operation																			
	Type of	3/8 in.		3/8 in.		1/2 in.		5/8 in.		3/4 in.		3/4 in.		7/8 in.		1 in.		1 1/4 in.		1 1/2 in.	
Size	Cavity	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
3 ft	Fine	35	65	40	70	45	75	60	90	70	105	80	105	95	120	120	150	145	170		
	Coarse					45	75	60	90	75	110	85	110	100	125	120	150	145	170		
	Extra Coarse									75	110										
4 ft	Fine	50	95	55	95	70	105	85	125	110	150	120	155	130	160	165	200				
	Medium					70	110	100	145	110	160	125	165	140	170	170	210	195	235		
	Coarse									115	175	130	175	150	185	170	210	195	235		
	Extra Coarse										175		175		185						
4 1/4 ft	Fine					95	135	105	155	125	185	145	190	175	220	205	205				
	Medium							120	175	135	200	155	205	190	235	215	260	235	280		
	Coarse									140	210	165	215	190	245	220	270	250	295		
	Extra Coarse															225	275	260	310		
5 1/2 ft	Fine							160	235	180	265	210	270	240	300	300	360				
	Medium													250	310	310	375	330	390		
	Coarse															315	380	340	400	400	465
	Extra Coarse																	350	410	420	490

Notes: 1. Net finished product passing effective screen opening.
2. Tons per hour passing through crusher including new feed and recreation load or override from effective screen opening.

Surges

The main objective of an in-process surge pile is to isolate the systems on both sides from each other. Without a surge pile, the normally erratic production rate coming from the primary crusher station can at one moment overtake the secondary station and moments later feed it nothing. The smallest surge pile to accomplish its isolation objective is one that does not quite run empty at any time during a normal production cycle. Larger surge piles provide operational flexibility on both sides of the pile.

Primary Crusher Surge Protection: In the previous section, the plant in the illustrative example was diagrammed to handle 500 tph. In actual practice, this plant would produce an average of less than 400 tph. Problems begin with the truck delivery system to the primary crusher. The haul distance and loading rates of trucks cause stone to be delivered at time intervals that rarely match the capacity of the primary crusher system. Also, some loads may contain mostly large size stone and others mostly fine sizes, altering momentary system capacity. Use of a large truck dump hopper with the capacity to hold several truck loads provides a surge between the truck delivery system and the primary crusher. In some operations, trucks dump in a shot rock surge pile near the primary station. The primary station is then fed by a mobile loader, in effect, creating a surge between the trucks and the primary crushing system.

Secondary Crusher Surge Protection: Primary crushers, even though designed to handle large quarry run material, often experience flow problems. Several large rocks may bridge in the opening to the crusher or a single large piece may lodge in the opening. In the plant illustrated in Figure 8.15, which is directly coupled from one stage to the next, a shut off of stone flow immediately affects the following stages. Plant productivity and product uniformity are improved by separating the primary and secondary stations with a surge pile, as shown in Figure 8.18.

One disadvantage of large primary surge piles is the high degree of size segregation that can occur, due to the broad size range of particles stored. Fine material stacks at the peak of a pile while coarse material rolls to the outside. When reclaimed, the fine material feeds in first, followed by the coarser particles. Pile segregation alone can have an erratic effect on succeeding systems. *In any event, a surge pile after the primary crusher should be included in all plant designs.* As a general rule, primary crusher stations should be sized at least 25 percent larger than the average desired production rate drawn from the primary surge pile.

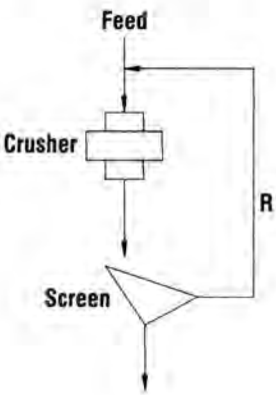
Surge Pile for Tertiary Crusher: Secondary crusher stations usually can be relied upon to produce at consistent rates when following a primary surge pile. Tertiary stations, however, must be sensitive to marketing conditions which dictate the amount of each size product produced. Since the final objective is to sell product, operators are compelled to produce what is in demand. Very often the resulting production rates are not the well-balanced flow sheet rates developed by plant engineers. Ingenuity and flexibility are required of designers and operators alike.

Table 8.8 Circulating Loads[8]

U_R Percent Undersize in Crusher Product	(r) Percent Oversize in Crusher Product	Screen Efficiency (e)						
		Percent 100	Percent 95	Percent 90	Percent 85	Percent 80	Percent 75	Percent 70
95	5	5.3	5.7	5.9	6.3	6.7	7.1	7.7
90	10	11.2	11.8	12.6	13.3	14.2	15.4	16.8
85	15	17.7	18.8	20.0	21.5	23.1	25.0	27.3
		EXAMPLE IN TEXT						
80	20	25.0	26.7	28.6	30.7	33.4	38.3	40.0
75	25	33.4	35.8	38.7	42.0	45.4	50.0	55.5
70	30	42.9	46.3	50.3	54.7	60.0	66.7	74.5
65	35	53.9	58.5	63.8	70.0	77.8	87.7	100.0
60	40	66.7	73.0	80.0	89.0	100.0	114.3	133.5
55	45	81.8	90.5	100.0	112.5	128.5	150.0	181.0
50	50	100.0	111.4	125.0	143.0	166.7	203.0	250.0
45	55	122.2	137.5	158.0	183.5	219.5	276.0	365.0
40	60	150.0	172.0	200.0	240.0	300.0	400.0	600.0
35	65	186.0	216.0	261.0	326.0	435.0	652.0	1,290.0
30	70	233.0	280.0	351.0	568.0	700.0	1,416.0	....
27.5	72.5	....	....	....	....	963.0	....	....
25	75	300.0	374.0	498.0	747.0	....	....	....
20	80	400.0	537.0	802.0		....	....	....
15	85	567.0	852.0	....		....	....	....

Note: Circulating load (R) is expressed in percent of original feed. Theoretical values will vary somewhat from actual circulating loads.

Examples

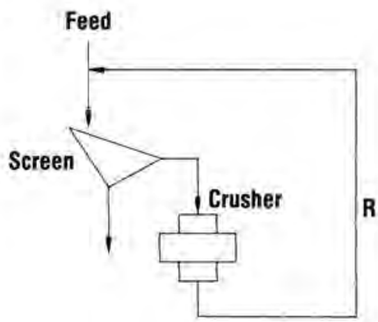


$$R = \frac{100}{\frac{e}{r} - 1}$$

e = 90% Screen Efficiency

r = 15% Oversize In Crusher Product

$$R = \frac{100}{\frac{90}{15} - 1} = \frac{100}{5} = 20\%$$



$$R = \frac{O_F \times 100}{e + U_R - 100}$$

O_F = 15% Oversize In Feed

e = 90% Screen Efficiency

U_R = 85% Undersize In Crusher Product

$$R = \frac{15 \times 100}{90 + 85 - 100} = \frac{1500}{75} = 20\%$$

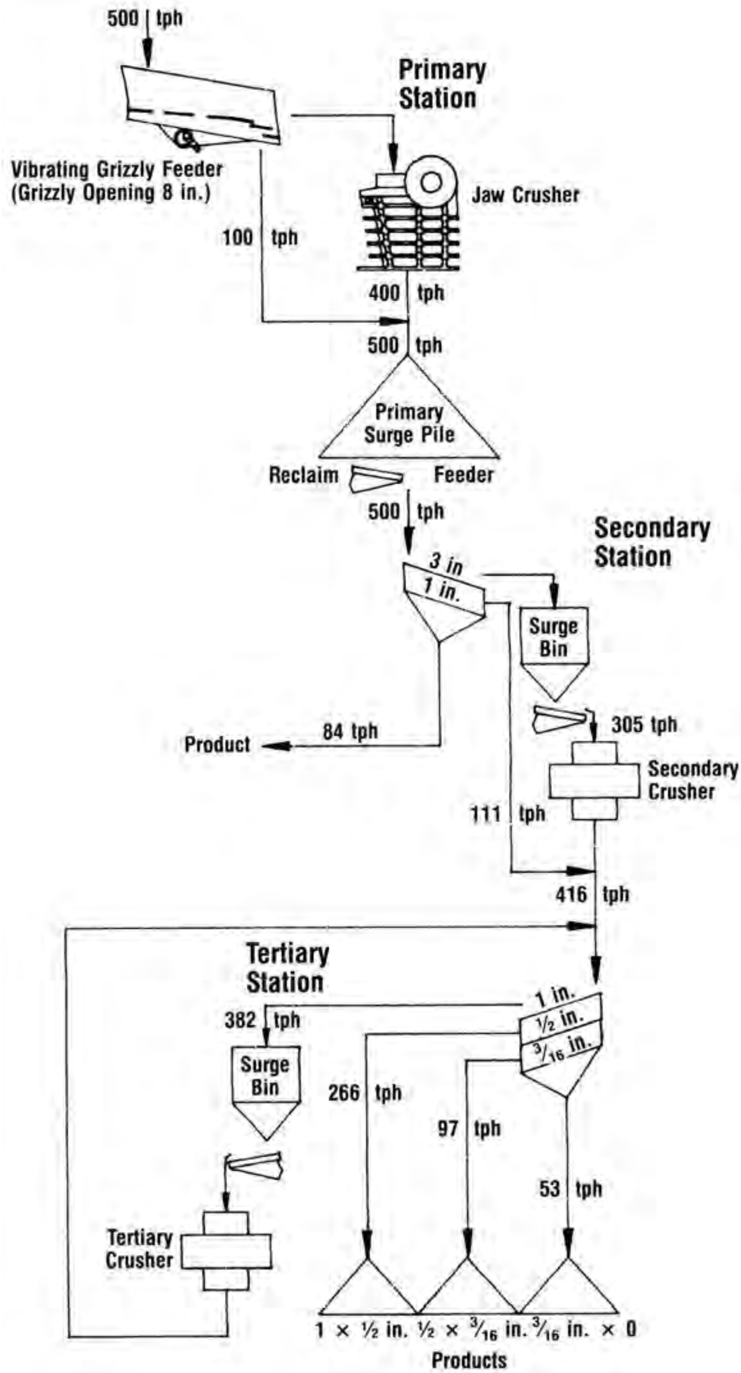


Figure 8.18 Typical 500 tph plant with primary surge pile and surge bins preceeding secondary and tertiary crushers.

In a directly coupled type processing plant, an event at one station influences the performance of other stations. For example, if the tertiary station is required to produce an unusually high percentage of finer products, the secondary station must run at partial load to avoid flooding the tertiary stage.

Some producers find it advantageous to separate the secondary and tertiary station with another surge pile, as illustrated in Figure 8.19. By separating each major production stage with surge piles, these segments can be operated at their own full productive effort without regard for production rate before or after each segment. This type of arrangement with the recommended surge bins preceding the crushers is much more amenable to automation. Also, higher product quality results due to consistent production rates. Flexible production schedules are useful in meeting market demands.

Fractionating

Fractionating is the process of screening finished product sizes into closely sized fractions. The fraction sizes are selected to facilitate subsequent blending to produce various gradation specifications required by the marketplace. In contrast to a plant design producing a product such as ASTM No. 57 concrete aggregates directly from a sizing screen deck, a fractionating plant produces closely sized basic fractions such as ASTM No. 5, No. 6 and No. 7 sizes. These basic sizes are then blended into the ASTM No. 57 gradation. The allowable gradations for standard aggregates sizes, such as No. 57 stone, are given in Table 11.1 of Chapter 11. A fractionating system is illustrated in Figure 8.20 as an extension of the plant diagram shown in Figure 8.19.

Type Plants: In some plant arrangements, sized fractions are held in bins just long enough to be blended into finished product sizes for inventory. In other versions, large quantities of sized fractions are inventoried over a reclaim tunnel. Feeders in the reclaim tunnel blend sizes onto a conveyor which feeds loadout bins. This style fractionating plant creates a centralized customer loadout station drawing product from open stockpiles.

A reclaim conveyor is quite useful in setting up recrushing systems to balance inventory needs. Large sizes are stockpiled over the reclaim tunnel for further reduction, sometimes on an automated basis during off-peak hours. Recrushing is more selective of the sizes to be recrushed, possibly improving desired product yield.

Advantages and Disadvantages: In summary, some of the distinct advantages of fractionating plants are as follows:

- Flexibility to respond quickly to various market demands and specifications.
- Improvement in quality control:
  - Stockpiling tightly sized fractions minimizes segregation.
  - Blending tightly sized fractions produces a more consistent product gradation.
  - Final rinse stations usually are incorporated into blending system loadout, assuring a clean product.

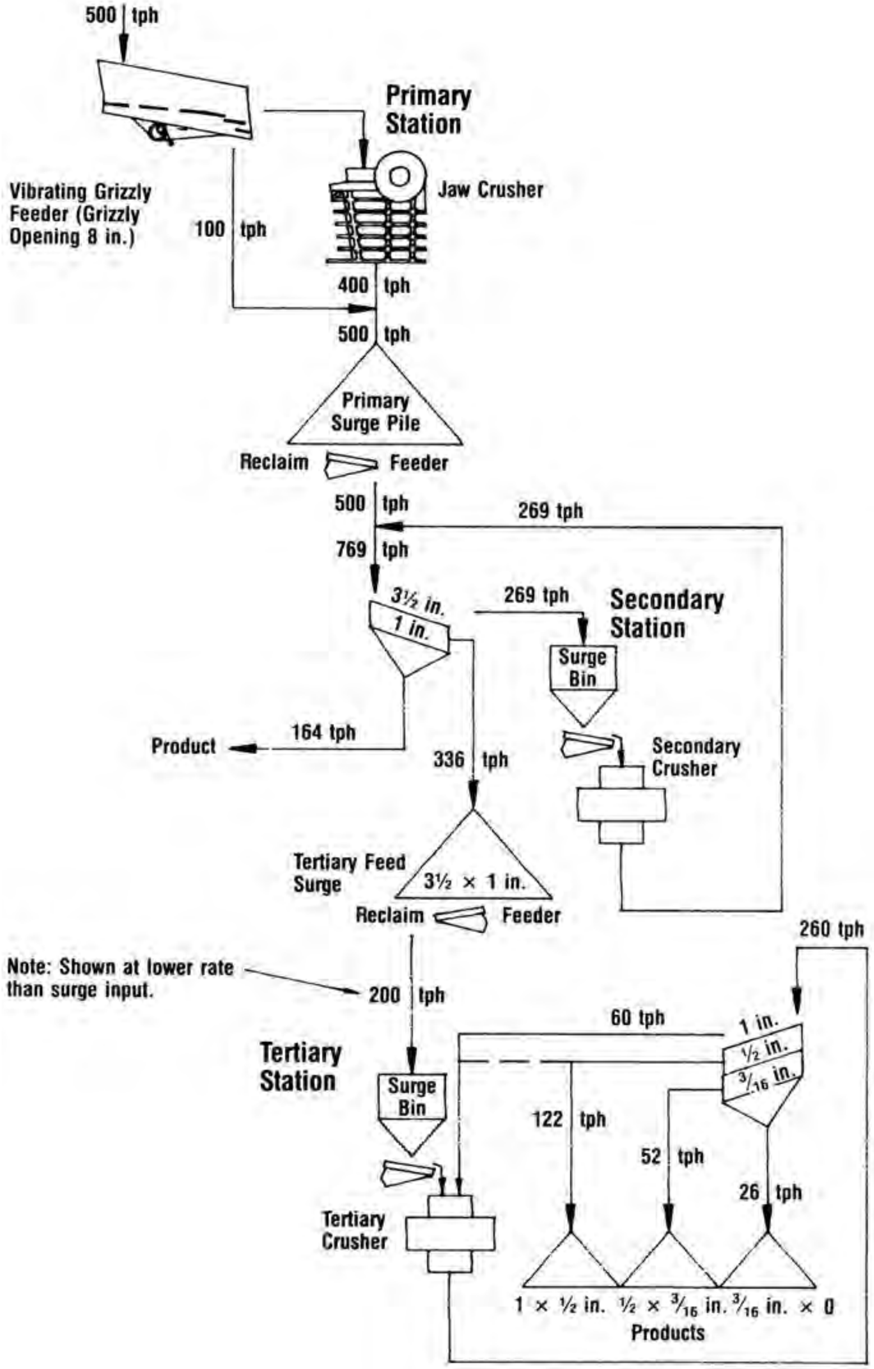


Figure 8.19 Segmented 500 tph plant with primary surge pile, tertiary feed surge pile and surge bins preceeding secondary and tertiary crushers.

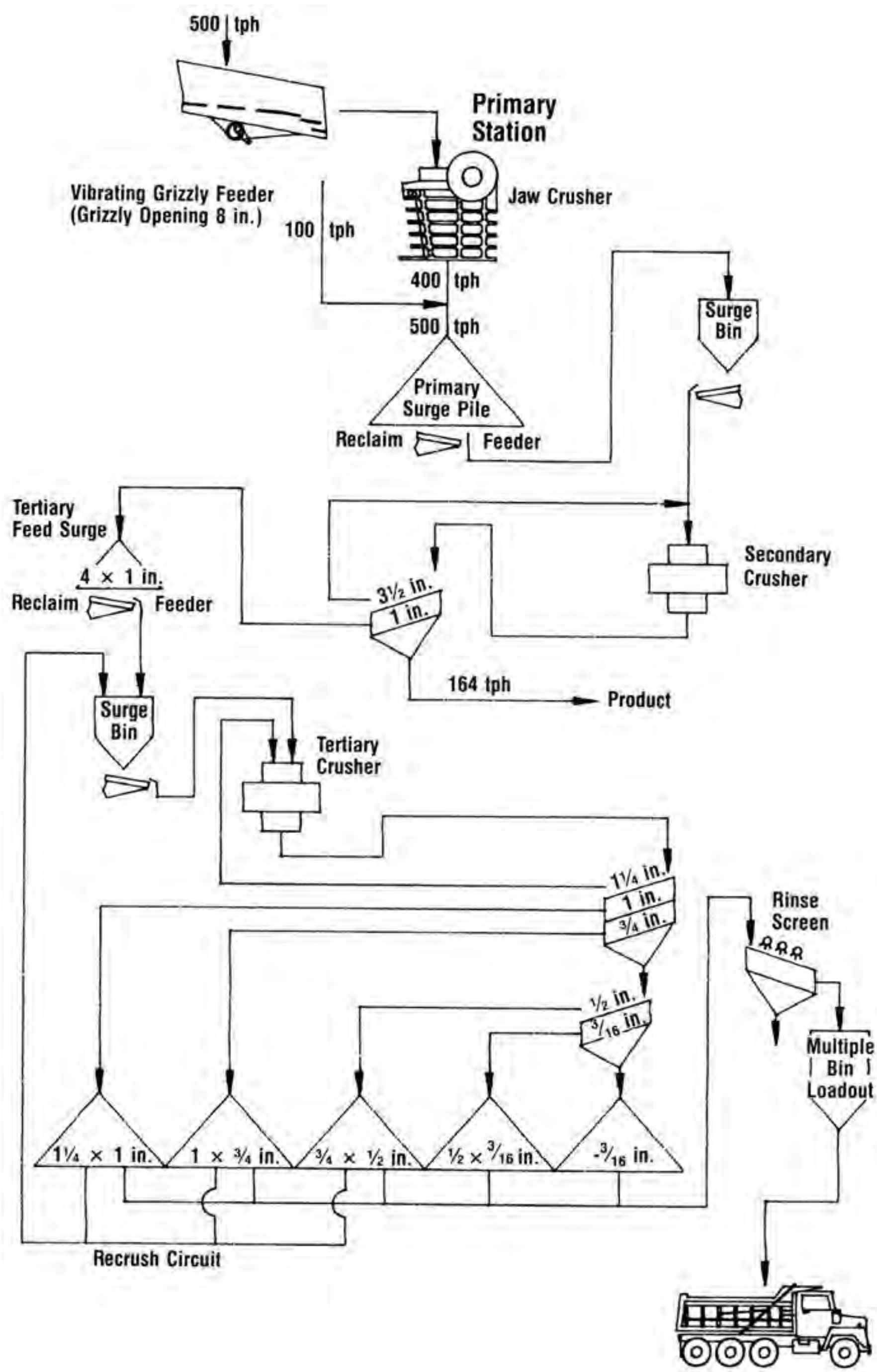


Figure 8.20 500 tph plant segmented fractionating plant.

- Automated loadout systems can be centralized for many products.
- Surplus coarse aggregates sizes can be reprocessed to control inventory.

Fractioning systems are costly to build due to the increase in the amount of equipment required for this type of system. If not planned carefully, frequent over-supply of intermediate sizes becomes an inventory and handling problem.

Reduction of Non-Marketable Fines

Introduction

For years, the aggregates industry has faced the question of what to do with excess production of *fines and micro fines*. The definition of fines, as used in this supplement to Chapter 8, is the minus ⅜-inch product resulting from aggregates production. Micro fines are minus No. 100 mesh material. The purpose of this supplement is to challenge the producer, through carefully controlled experimentation, to reduce the production of undesirable product in the processing facility. The question of what to do with excess fines product is not considered here, but has been the focus of numerous papers. Markets for these products require intense investigation and creativity to match current supply. However, what if the producer is able to reduce the percentage of undesirable fines in the total aggregates production process? This chapter provides some potential avenues of investigation that the producer can pursue to potentially reduce fines production.

Before considering reduction in fines production, the reader should first become familiar with the following sections of *The Aggregates Handbook*: Chapter 3 that covers geologic aspects of the crushed stone industry; Chapter 8 that gives an informative introduction to crushed stone processing systems; and Chapters 3 and 11 that discuss specifications of end product.

The quarry industry, which has supplied the market over the past several decades, has gradually undergone an important shift from high levels of basic stone production for construction of new highways to a much wider product mix. One important focus of aggregates production is now on rebuilding and resurfacing the existing highway system. Federal, state and local transportation officials actively have been involved in the development of improved aggregates specifications. As a result, specifications have in general moved toward cleaner products and fewer fines to obtain increased life in the final product. Improvement in concrete and asphalt quality has been achieved through tighter material specifications including cleaner aggregates products. As a result, the producer must change with the times and focus on how to produce what the customer wants in an economical and efficient manner.

Overview of the Operation

Baseline: The aggregates producer must look at his total operation from the quarry or pit face to the finished product and every phase in between. A baseline of current operating procedures and processes must first be established. The producer should carefully examine the geology of his deposit and the current drilling and blasting techniques (or ripping, digging and loading procedures if blasting is not required). Once the shot or ripped rock is introduced into the processing facility, the producer should analyze each crusher discharge for aggregates gradation, tonnage and aggregates shape. These findings should be compared with the original equipment manufacturer's (OEM) specifications for the equipment used. Each screening unit, or series of units, should be analyzed including its efficiency and ability to handle the crusher discharge. Improper methods of aggregates stockpiling also can amplify fines production problems. Hence stockpiling techniques should be examined. Finally, the producer should determine if the customers' demands and specifications are being met. Establishment of the above baseline is essential in determining if the resulting changes in aggregates production made by experimentation are successful.

Geology: A detailed examination of the deposit geology may benefit the producer in both the blasting and crushing operation. Whether the producer is in limestone, granite, sandstone, Traprock or other formations, including sand and gravel deposits, the characteristics of the deposit aids in understanding how the rock crushes. The producer should determine whether the material is (1) igneous, sedimentary or metamorphic, (2) fine or coarse grained, (3) massive or highly laminated, (4) friable and (5) sound. Each of these material characteristics assist in explaining the end aggregates products produced. Using this information, a producer can work closely with the geologist and drilling blasting company to determine the best method of blasting the face to obtain optimal rock breakage. Drilling and blasting is an experimental process and procedures may vary from face to face and also vary with depth in the quarry as rock characteristics change. Information to assist the producer in achieving optimal breakage is increasing with the growing expertise of geologists and explosives companies and the development of sophisticated computer simulation programs.

Drilling and Blasting: Frequently, drilling and blasting is performed using an outside specialist rather than in-house personnel. A specialist drilling and blasting company can offer expertise in analyzing the best use of their products. The final aggregates product including percentage of fines is influenced by the type of explosives used, quantities of explosive, along with the blasting hole spacing and depth of hole and overburden. Weather conditions along with whether the blast hole is wet or dry can greatly change end product production. Experimentation with the blasting operation must be closely monitored due to the potential liability and neighbor complaints.

Primary Crushing

Blasting of the rock results in a pile of stone called the *muck pile*. The muck pile material is transported by truck, loader and/or conveyor to the processing facility where it is loaded in to the crushing circuit. Primary crushing in large quarry operations is sometimes accomplished with a *gyratory type crusher*. The gyratory crusher is capable of handling direct dumping from truck to crusher. A grizzly feeder can be employed to allow bypass of material that is smaller than the crusher closed side setting. *Jaw style or horizontal impactor style primary crushers* usually are fed by a vibrating or drag style feeder. A vibrating feeder can employ a grizzly section on the discharge end of the feeder. The openings on the grizzly are adjusted to allow undersize material to bypass the primary crusher, resulting in increased primary crusher productivity and reduced secondary breakage in the primary crusher. In some primary installations a scalping screen is employed in front of the primary crusher to accomplish the same benefits as the grizzly section in the feeder.

Optimum Capacity: In most cases a crusher functioning at or near the OEM capacity produces better particle shape and reduces particle elongation than if operating at less capacity. The producer should utilize the OEM to make trial recommendations on crusher settings and speed for both styles of crushers. Numerous types of crusher liners are available for the jaw crusher. Both OEM and after-market suppliers of manganese liners can provide insight into a proper liner combination. Extensive experience in various stone production applications and rock types is of great assistance in the process of proper liner selection. Establishing a benchmark of the current operation is important so that change in production (e.g., capacity, gradation, particle shape) can be evaluated properly. The producer should also investigate the effect of one change at a time. Otherwise, a desirable change may be cancelled by an undesirable one. It is important to maintain similar operating conditions for all evaluation tests. The optimum operation has a pile of aggregates, called a *surge pile*, following the primary or secondary crusher operation. Use of a surge pile provides a consistent feed to the remainder of the plant and improves screening and crushing efficiency. Reduction of fines and micro fine products can be improved even at the early stage in the process.

Secondary and Tertiary Production

The secondary and tertiary aggregates crushing facilities receive feed either from the surge pile or directly from the primary crusher. The producer should analyze the current crusher and screen set up in the plant to determine if there are any choke points in the plant related to the screens. In a properly designed plant, the crushers are the choke point. To optimize the crushers, a surge bin with 6 to 10 minutes of live storage provides appropriate material to offset variations in aggregates gradation of the surge pile.

Various types of rock crushers are utilized for secondary and tertiary crushing. These crushers include, but are not limited to, cones, gyratory, horizontal impacts, jaws, vertical shaft impacts and roll crushers. Each crusher has advantages in specific applications. A few key items that should be discussed with the OEM include crusher aggregates reduction ratio, crusher speed stroke and rock material characteristics. *Aggregates size reduction ratio*, coupled with controlling top size feed, play a very important part in fines production. Aggregates size reduction ratio is the ratio of the maximum size rock going into the crusher divided by the maximum size of the aggregates coming out. Appropriate aggregates reduction ratio ranges from 2 to 1 up to 8 to 1. As a general rule, the higher ratio results in increased fines. A feed size that is too large can greatly reduce crusher capacity and have adverse effects on product quality and shape. Having the OEM test the actual rock to be processed provides insight into potential gradation and shape characteristics of the aggregates. Hence, if possible, conduct full-scale field crushing tests in the operation. Field and lab test results, however, often do not provide the same results.

Crusher Speed and Stroke

Speed and stroke of the crushers play a major role in fines productivity. Variations of crusher stroke combined with crusher speed have changed the recent recommendations of cone crusher manufacturers. Test results tend toward increased productivity in smaller units and decreased percentage of fines and micro fines as a function of total production. Gradations of products obtained from both vertical and horizontal impact crushers are greatly influenced by crusher operating speed. A decrease in operating speed generally results in decreased fines as a percentage of total production. In the case of the vertical shift impacts (VSI) crushers, the configuration of the table with four to six shoes or discharge openings from a rotor has a dramatic effect on fines production. The VSI crusher has benefited from recent metallurgical advances that increase wear part life as a result of decreased wear. The best end result aggregates products for the least cost of operation is achieved by carefully reviewing the combinations within the crusher of metal to metal, rock to metal, metal to rock, and rock to rock. Product shape from the VSI crusher is very good (i.e., minimizes the production of flat and elongated particles). A properly fed cone or gyratory crusher also gives good particle shape. A roll crusher tends to give good particle shape at low reduction ratios. Both primary jaw crushers and cone crushers have multiple liner configurations. Experimentation coupled with supplier knowledge leads to the proper configuration of liner. In summary, experimentation with the crushers used in production is crucial to optimizing product mix.

Screens

To set up an aggregates production facility properly, screens should be analyzed for proper size to maintain the choke-point at the crushers. Location of the choke-point at the crusher results in a consistent product. Each screen should be analyzed to determine optimum speed, stroke and type of screen media. Removal of fines from marketable product is greatly enhanced if the feed to the screen is consistent and the correct stroke, speed and screen media are used. The OEM can assist with evaluation of the screens. Moisture in the screen feed can dramatically change the efficiency of the screen media and may need to be corrected.

Additional Fines

An overall good aggregates production process flow can be improved by reviewing these basic suggestions. Knowing the production characteristics of the current process aids in evaluating each proposed change. A poorly conceived plant design will not improve until the existing design flaws and choke points are eliminated.

Manufactured sand production in crushed stone facilities can develop into a source of additional micro fines. Depending on the marketplace, production of stone sand can be an outlet for ⅜-inch minus fines. If the producer's ⅜-inch minus fines is of suitable quality, shape and soundness, then achieving the required gradation becomes the primary concern. For some producers the desired gradation, which requires a certain body in the middle of the grading curve, can result in creation of additional micro fines in the crushing circuit. For the product to meet the specifications, the key particle sizes usually occur in the product between the No. 16 mesh and No. 50 mesh screens. Also, the reduction of minus No. 200 mesh particles must be achieved. Many producers have to screen on No. 4 to No. 8 mesh screens to have enough No. 16 x No. 50 mesh material in the product. This screening creates excess No. 200 mesh material as a by-product. Removal of No. 200 mesh product has come a long way in recent years from simply washing micro fines out of the product to the use of modern negative air pressure systems that suck micro fines off from the dry product. These dry micro fines can then be considered for other applications.

Manufactured Sand Production

Before developing an expensive capability to produce manufactured stone sand, the quarry operator should evaluate the following factors:

1. The cost of current disposal techniques;
2. The cost to produce a stone sand product;
3. The willingness of the market to accept a manufactured stone sand; and
4. The estimated revenue to be received for the stone sand.

After performing this study, the producer can then make a thoughtful financial decision on the viability of a manufactured stone sand operation. The crusher and screen evaluation techniques discussed in the preceding secondary/tertiary processing section can be applied to stone sand processing facilities. The dry screening of stone sand utilizing high frequency screens is a viable, efficient alternative to those of conventional screens. The OEM suppliers are very helpful in these evaluations.

Stockpiling

The producer of the aggregates product must recognize the impact of stockpiling methods on aggregates gradation. Secondary breaking of aggregates during stockpiling and stockpile segregation can cause a perfectly good product to be out of gradation or even shape specification. Training employees properly on the importance of stockpile management can eliminate many potential customer complaints. Maintaining correct gradation is helped by employing the proper equipment such as a rubber-tired bulldozer instead of a track machine or an elevating stacker instead of a fixed unit. Aggregates segregation is considered in detail in Chapter 8, Section 8.4.

End Use Specifications

A proactive producer of aggregates products must understand and take into consideration the specifications and desires of the end user. In some cases specifications can be altered to decrease production costs and improve the end user's satisfaction. For example, some state department of transportation agencies have recognized that an increase in percent passing the minus No. 200 mesh screen for manufactured concrete sand from 0 to 4 percent passing to 0 to 7 percent passing does not have a negative effect on strength. Indeed, in many cases this gradation change has a positive effect on strength. Proactive producers worked hard to obtain this desirable specification change which decreases the excess volume of micro fines produced that would have had to be handled and either marketed or disposed of.

8.15 Special Products

Special products are produced as the exception rather than the rule. Small quantities and higher selling prices are characteristics of most special products. Even though these products command higher selling prices, they are seldom big profit items. The special plant modifications, potential overall production loss and special handling required for special products normally increases the production costs significantly.

Armor Stone: Armor stone is used to construct jetties to prevent erosion due to the action of large waves. Boulders weighing 2 to 8 tons are selected from the pit run by a crane operator or a front-end loader specially equipped with a grapple. When large quantities of armor stone are required, special blasting techniques are employed to produce a greater yield of the desired size. Use of these special blasting techniques often unfavorably impacts the recovery cost of the remainder of the shot due to the predominance of large size material.

Riprap: Riprap is employed to stabilize slopes and shorelines, build erosion control structures, construct buildings and improve landscaping. Riprap usually has a set of tightly controlled specifications developed for each job. Average riprap sizes vary from 6 to 30 inches. Riprap is produced by several innovative methods. When utilizing typical aggregates processing equipment, riprap is top-sized by setting the primary crusher to the maximum allowable opening. The crusher product is discharged onto a vibrating feeder or an oversize, heavy-duty conveyor belt that transports the material to a large heavy-duty scalping screen or grizzly. The riprap is produced from the screen or grizzly top-deck discharge.

Riprap Plants: In some cases where product demand warrants, a riprap plant is set up in the pit. Riprap plants are capable of producing multiple stone sizes utilizing large grizzly feeders placed before and after a specially designed jaw crusher. For a typical flow the jaw crusher discharge (top size up to 24 inches) is placed onto a feeder with grizzly openings set at 12 to 18 inches. The material passing over the grizzly is a coarse product. The material passing through the grizzly proceeds to a heavy-duty sizing screen making separations at 12 and 6 inches. The zero to 6 inch size excess is normally processed into aggregates sizes in the finishing plant.

A self-contained portable scalping screen or grizzly set-up also is used to produce riprap in the pit near the shot rock pile. Front-end loaders feed these units to remove the fines with top-size being controlled by the loader operator. Specifications are difficult to meet using these portable units.

When the gradation is not critical, a front-end loader bucket having a grizzly-like bottom can be used to remove the fines. Again, the top-size is controlled by the loader operator. The fines removal is less efficient than a grizzly unit and additional effort is needed to clean up the fines left on the pit floor.

Gabion Stone: Gabion stone is used to fill galvanized, woven steel wire baskets which are utilized for erosion control and retaining wall construction. The first screen in a plant circuit is usually a good place to produce this 4- to 8-inch size stone. It can be removed as gabion stone or can be fed to the secondary crusher.

Aglime: Aglime is a fine limestone product used by farmers to neutralize acidic soils. Aglime specifications vary widely from state to state, but all states require a product passing the No. 8 screen. Aglime requirements and specifications are discussed in Chapter 14. Many aggregates plants produce aglime as a by-product. When produced as a by-product, the only additional plant equipment required is a screen. Additional crushing equipment can be utilized to supplement production of this material when the market dictates. Aglime crushers are typically high-speed mills having high horsepower requirements. The raw feed to the mill impacts against a selected grate or screen to produce a finished agleam in open circuit. Aglime is commonly produced using a hammermill, cage mill, ball mill or rod mill. Vertical impact crushers have been used in a supplemental circuit, but require a screen to remove the product.

When market requirements exceed by-product plant capacities, a plant devoted to aglime production becomes feasible. These plants usually include a dryer to remove moisture prior to the raw feed entering a roller mill. Some mills are equipped with a negative pressure to regulate flow and gradation. A finer, more tightly graded aglime is produced by these plants usually consisting of a minus No. 20 sieve size product. The plants utilize bins to blend various grades of aglime and add supplemental products such as magnesium. A pug mill may be employed to provide uniformity and additional moisture during shipping.

Moisture: Moisture content is a critical consideration in selecting crushing, screening and conveying equipment for aglime. Capacities and gradations are significantly affected by moisture content. Equipment manufacturers' recommendations and historical data from similar applications are the best guides for determining the proper equipment selections.

8.16 In-Pit Conveying and Crushing Introduction

As in-pit truck haulage costs escalate with increased distance and elevation change from the working faces to the primary crusher, aggregates producers should consider alternative transportation systems. A belt conveyor system, which can use a more direct and steeper route than trucks, is one of the most attractive alternatives. The primary crusher station located in the pit can be stationary or have varying mobility characteristics.

The cost to operate a stationary primary crusher in the pit or remote from the pit is the same. The in-pit truck haulage costs are reduced when the primary station is located in the pit compared with the higher costs for truck haulage to deliver shot rock to a primary station remote from the pit. In this case a direct comparison can be made of truck haulage compared to a combination of in-pit truck haulage and in-pit conveying. In evaluating other alternatives, the comparison becomes more complex.

To incorporate an in-pit conveying system in most quarries, a primary crusher precedes the conveying system to control the lump size to reduce maintenance and utilize economical conveying systems. The combination of location and type of primary crusher station and design of in-pit conveying systems must complement the quarrying operation and meet the objective of the producer. Depending on the selection of the in-pit crusher and conveying system, this type of system can completely eliminate truck haulage or truck cycle times can be shortened dramatically, with a commensurate reduction in the size of the truck fleet. Older and less efficient trucks may be eliminated, and maintenance problems with the remaining fleet substantially reduced with a large part of the punishing vertical lift eliminated from the truck haul.

The four cost areas in which conveying enjoys the advantage over truck hauling are personnel, maintenance, energy and capital replacement. The reduction of truck drivers and repair persons represents the largest part of the cost savings associated with using belt conveyors.

Types of Mobile Crushers

Most of the commercial mobile crushers in operation in the aggregates industry are designed for crushing limestone or granite, and have a theoretical output of 100 to 1,500 tph. A few larger units, which are designed for particular applications, have outputs of 2,000 to 5,000 tph. Mobile crushers of even larger capacity are in use in Europe and the metal mines in the western United States with capacities up to 10,000 tph.

Direct Feed: The type of primary crushers mounted on the mobile units can be jaw, gyratory, hammer mill, impactor or roll type crushers. Mobile crushers are either the direct-feed or indirect-feed type. Direct-feed mobile crushers receive the material from shovels, back-hoes or front-end loaders without using a feeder. An access ramp is used if the loader cannot reach the top of the receiving hopper. The ramp can be part of the crusher assembly, moving together with the unit, or it can be an independent structure, moved on skids or on crawlers.

Indirect Feed: Indirect-feed crushers receive the material from inclined feeders, usually of the heavy-duty, apron type. In most cases, the receiving hoppers are located at a lower elevation than the crusher inlet, and the material is fed into the feeder hopper at ground level by the excavator(s).

Mobile Crusher Design

Like all mobile machines, mobile crushers must be designed in a relatively compact form and as lightweight as possible. The experience of the manufacturers is vital to the success of the mobile crusher design to achieve the proper balance between compactness and portability while having good performance and handling characteristics. Accessibility and maintainability of the system must be considered in evaluating overall cost effectiveness of the system.

Mobile primary crushers can be moved within the quarry at speeds of about 200 to 300 fph and can negotiate grades up to 10 percent. Mobile crushers employ a variety of mechanisms which make movement possible, including rubber-tired wheels, crawler tracks and walking pads. Crushers utilizing synchronized walking pads can be controlled from a central console. The walking pad system is highly reliable, simple, economical to operate and maintain, and usually is the least expensive for a given production capacity.

The design applications for mobile crushers are as varied as those available for fixed layouts. Many designs can be successfully used if the resulting overall configuration is economical. The typical mobile crusher layout comprises the following equipment, as shown in Figure 8.21.

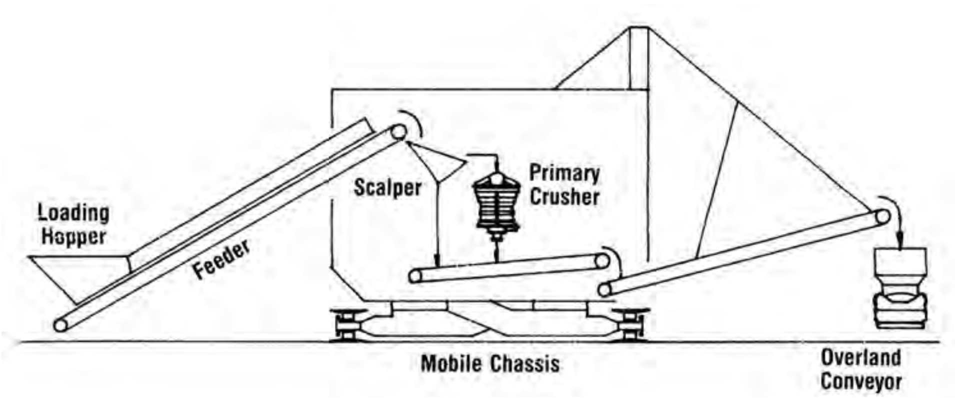


Figure 8.21 Typical mobile primary crusher.

Feed Hopper: The feed hopper must be sufficiently large to safely contain the load delivered by the feeding unit. The feed hopper is usually sized to handle two or three bucket loads or 1 ½ truck loads of material. The hopper size is dependent on the throughput capacity, expected excavator cycle times and possible truck delivery cycle factors.

Crusher Feed System: A feeding device is normally necessary to transport the material from the feed hopper up to the mouth of the crusher or the optional scalping screen. The most common method of feed is the use of an apron conveyor. Apron feeder design for this application must be extremely heavy-duty and easy to repair. Recent designs have tended to use standard tractor chain components which are rugged and readily available. The apron feeder is commonly provided with a spillage collection conveyor underneath to minimize cleanup. The biggest influence on the size of the apron feeder is the size and type of crusher used. A tall crusher, such as a gyratory, requires a very long feeder that adds to the cost of the unit.

Scalping Device: Additional capacity is achieved by scalping the quarry fines ahead of the crusher by means of a vibrating or reciprocating grizzly. Since the weight of the mobile unit is most sensitive to the size and type of crusher, certain applications exist where a smaller primary crusher, preceded by scalping, is more economical to meet design capacity parameters than a large crusher without scalping provisions.

Crushing Unit: The crusher is the heart of the mobile unit and determines the overall design parameters. Its selection is based on the type of material being handled, the required throughput tonnage, the size of the product and the desired operating cost. *If a particular application permits the use of more than one type of crusher, preference should be given to the unit with minimum weight and minimum overall height.* These facts, more than any other, affect the overall unit configuration. The expertise of the crusher manufacturer is vital in providing a layout where each aspect of service and repair is considered, given the space limitations.

Crusher Discharge Conveyor: The scalped material that bypasses the crusher and the product through the crusher is collected and moved to a position where it can be discharged to the loadout conveyor. The discharge conveyor depends on the type of crusher used and can be a conventional rubber belt or an apron conveyor if large impact forces are expected.

Loadout Conveyor: The loadout conveyor transports material from the discharge conveyor and delivers it to another conveyor system, into trucks or to a stockpile. This conveyor can be of a fixed configuration, but in most cases swings from side to side to provide flexibility between the frequently moved crusher and relatively fixed conveyor system. The features of this type of conveyor are specially designed to effect compromises between space and flexibility to adapt to the particular material handling system employed.

Auxiliary Equipment: The auxiliary equipment used with a mobile crusher is similar to that found on fixed installations. Auxiliary equipment includes air compressors for operating equipment and maintenance, rock breakers for clearing the grizzly or crusher chamber, and magnets and/or metal detectors for removal of tramp material. Other equipment normally provided includes hoists for maintenance and a diesel generator for moving or servicing the crusher independent of external power supplies.

Selection of Mining System

The mobile crusher station does not stand alone and is only one part of a complete mining system. When a moveable crusher-conveyor system is introduced into a mature open-pit, a complete and probably drastic re-evaluation is required of the mining plan. All aspects of the pit design, including rock mechanics, mining sequencing and potential pit expansion, must be thoroughly reviewed before a decision is finalized.

The quarry benches must be as long as possible and the face height as high as possible. This mining approach utilizes the mobile crushing plant in a suitable way and achieves the economics of eliminating haul trucks, operating and maintenance personnel, road construction and maintenance, etc. To reduce the frequency which the crusher location is changed, the bench widths must normally be enlarged. Mobile crushers can best be used when the following geological and mining conditions are present:

- The deposit is laterally continuous without significant faulting or other discontinuities; and
- The configuration of the deposit permits sufficiently long working faces and the rock structure allows sufficiently high faces.

A study of 115 German quarries[10,11] compared haul truck to in-pit crushing systems. The conclusion reached was that for almost every open-pit quarry with an output of at least one million tph, the in-pit crushing system is more advantageous. In the 1980s, the Mobile Crusher System had limited acceptance in quarries in the United States. Now mobile in-pit primary units are common-place and have found their place. Since each situation is different it is important to weigh the pros and cons of each type and position of crusher within the operation. Trying to predict future production demands as well as deposit extraction also will influence the final decision.

8.17 Automation

Guide to Successful Automation: Experience has shown the most successful automation projects are those that use automation as a tool to obtain results and benefits to optimize plant efficiency. Different levels of automation can be employed and different degrees of success achieved. Many conventional plants were built without following the known fundamentals and proven principles of good plant engineering necessary to achieve optimum production in a competitive market. An appropriate saying is "*If you attempt to automate a mess, you get an automated mess!*" This summarizes most of the past application problems.

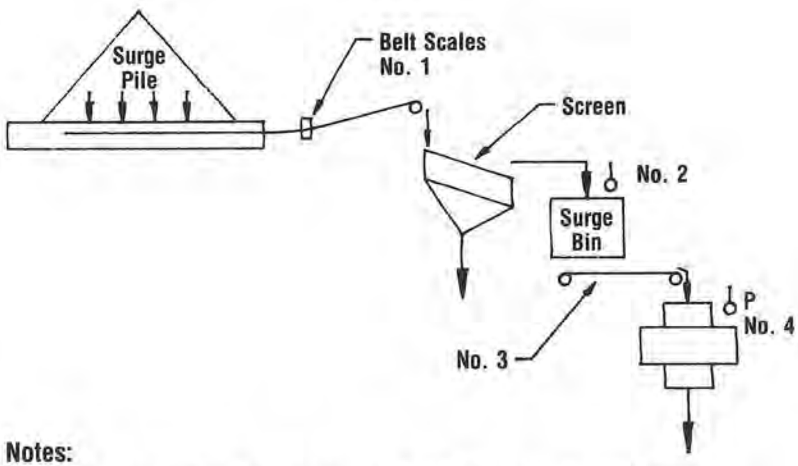
One of the pioneers in successful plant automation used simple, easily maintained controls for automated plant operation as the finishing touch to achieve optimum plant production. This company succeeded using automation because their plants were engineered into self-balancing, easily automated segments. As a result, extended operating hours were possible with minimum operator attention.

Simplifying the processing plant is a prerequisite to effective automation. Dividing the typical in-line crushing plant into segments separated by adequate surges is one way to simplify the process. Automated systems that are integrated into a well-designed plant result in a higher level of plant performance.

Automating an Existing Plant: Knowing where to start automation within an existing plant requires a systematic study of the process. An in-plant testing program is the best method to study the process. The performance of the existing plant should be monitored and the plant modified as required to eliminate bottlenecks. Experience has proved that best results are achieved by making one change at a time. Monitor the results of each change with a series of tests. Proceed when the change produces positive results and crease when the change is counterproductive. Complete all the plant improvements.

Various viewpoints exist on how to automate an existing stone plant. Many operators have been successful by first achieving optimum production in the manual mode. Operating in the manual mode should achieve approximately 85 percent of the optimum plant capacity. At one finishing plant located in the southern United States, an automated process system increased the capability by 14 percent over that achieved in the manual mode by a conscientious operator.

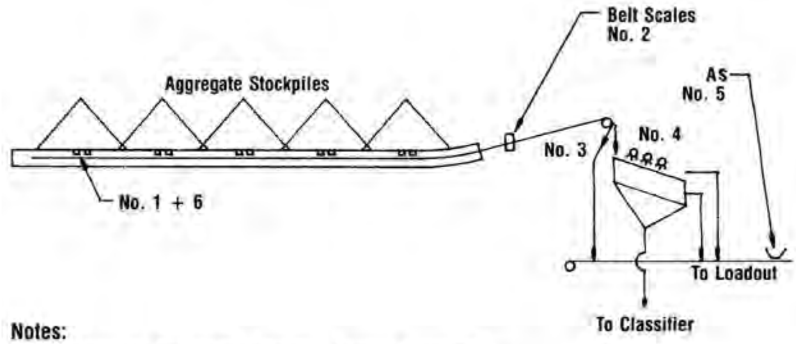
Levels of Automation: The simplest rules to follow are "Don't automate anything you can't control" and "Monitor and automate everything you need to control." The most desirable level of automation to achieve must be determined on a case-by-case basis. Many automation schemes are designed into existing control and monitoring systems. Figures 8.22 and 8.23 illustrate several alternative schemes for achieving automation for a crusher feed control and blending system.



Notes:

1. **Belt scale to monitor plant production rate and accumulated totals.**
2. **Level control for surge bin to control rate of feed from reclaim feeders from surge pile.**
3. **Variable speed belt feeder to control feed to crusher.**
4. **On cone crushers use level and power control to monitor and control rate of feed to crushers. On impact crushers use power control to monitor and control rate of feed to crusher.**

Figure 8.22 Typical crusher feed control.



Notes:

1. **Slide gate feeder for blending coarse aggregate.**
2. **Belt scales to calibrate slide gate feeders rate of flow with various coarse aggregate sizes. Also scales are used to monitor if blend rate of feed is within acceptable tolerance.**
3. **By-pass flop gate for dry coarse aggregate.**
4. **Rinsing screen for rinsed coarse aggregate.**
5. **Automatic sampler for retrieving samples for quality assurance monitoring.**
6. **Blends are established by experience resulting from monitoring the quality assurance program.**

Figure 8.23 Typical blending system.

Most successful automation schemes include using programmable controllers and/or computer-based hardware. The level of automation can extend to a completely automated process, assisting the operator in achieving the highest plant operating efficiency. The sensor equipment and monitors controlling the process must be selected and installed to assure the reliability necessary to minimize unscheduled downtime. The interlocking of equipment in the process is controlled by a software program.

The equipment used in an automated plant should have proven field performance and reliability. Work with companies and manufacturers that have provided reliable and proven hardware, software and sensory devices. Finally, visits to processing plants that have been successfully automated are most beneficial.

Economic Justification: Unless the required changes in plant and the cost of automation have a favorable rate of return on the necessary investment, automation is not feasible. Each level of automation must have economic justification.

Quality Control and Automation: Increased productivity can be achieved by automatic feed controls under the proper conditions. A constant feed to the crushers at the highest production rate can be controlled by monitoring by sensors from the power load on the crusher motors and/or by level control of material in the crushing chamber (assuming a cone crusher is used). Automating the crusher circuit also can produce a higher quality stone with respect to particle shape and gradation.

If the screens receive a constant feed from the crusher as a result of automating, the material gradation will have a minimum variation. The bed depth and rate of flow of material across the screens will be constant. Screening efficiency also will be constant and the circulating load stable. The finished products from the screens will maintain a closer tolerance to the specifications as a result of automation of the process. Automatic samplers can assist with quality control within the processing plant before the materials are stockpiled. Automatic samplers can be utilized at loadout for quality assurance testing.

Summary: The automation process should be implemented by combining a thorough knowledge of the processing requirements with the knowledge of electronic or electrical technology. Good plant engineering and in-plant testing is the foundation to a successful automation project. A major producer's flow chart is shown in Figure 8.24.

The world of aggregates production is becoming more complex. To be successful, aggressive plans must be developed to overcome stiffer competition, tighter government controls and an ever changing product mix. The competitive edge and rewards will go to the producer who best addresses each of these areas.

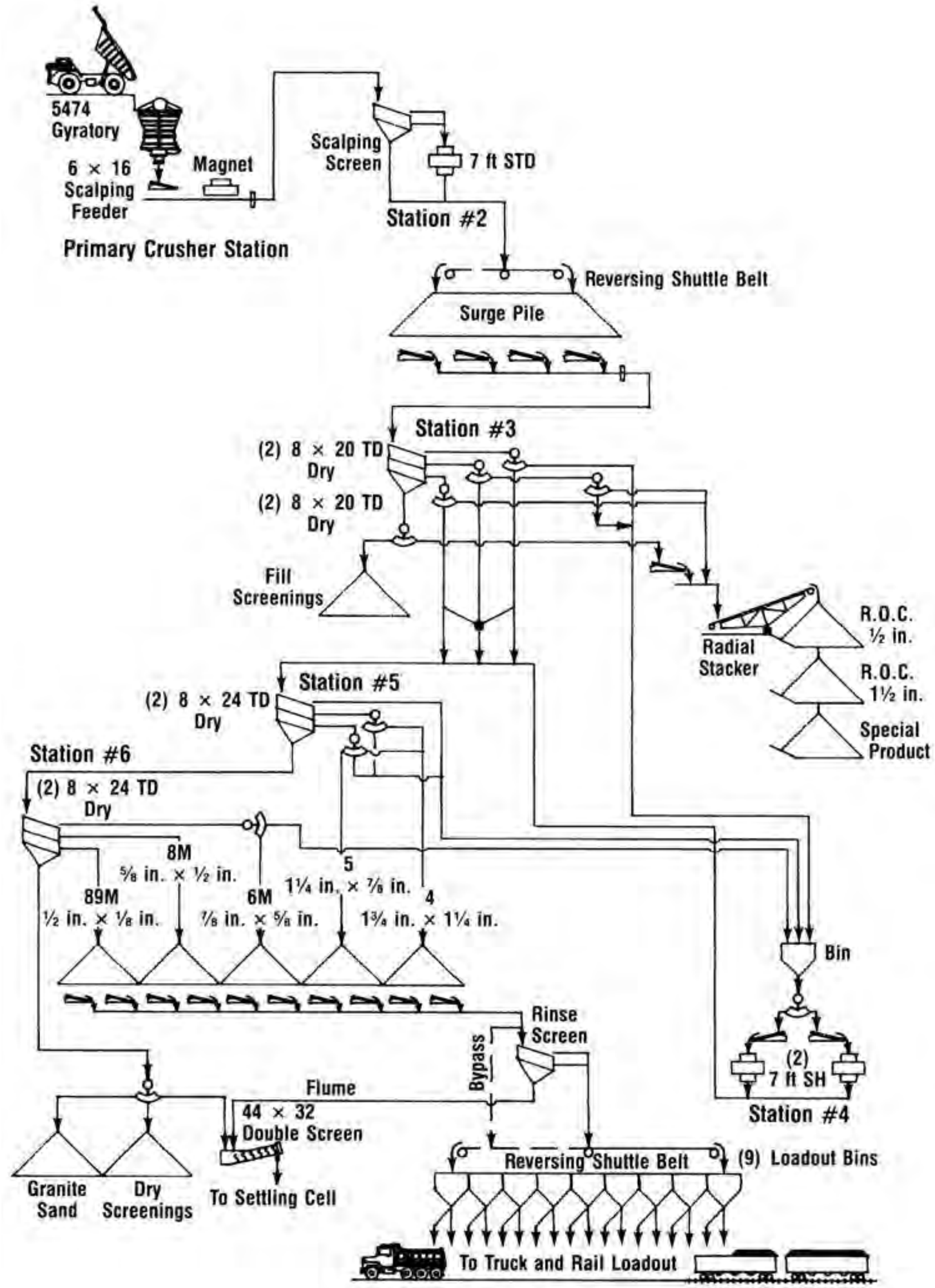


Figure 8.24 Typical blending system.

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Chapter 9
The Marketplace

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First Edition
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9.1 Market Development and the Sales Organization

Definition of the Marketing Function in the Aggregates Industry

The Evolution of the Aggregates Industry: The aggregates industry is evolving from small, family-owned businesses to an industry that is merging and consolidating into large firms with national and international ownership. Because of this consolidation, the successful aggregates firms now have large financial bases and sophisticated management skills.

Primarily, consolidation is a result of the high cost of entry into the aggregates industry. Large capital investments in plant and reserves are required to achieve economies from high production capacity. Local, state and national governmental policies that require companies to comply with wide ranging and frequently inconsistent sets of governmental regulations also contribute to the trend toward consolidation. A highly trained technical staff is needed to monitor, negotiate and respond to the requirements of the increasing number of governmental regulations. This present condition contrasts dramatically with the early aggregates industry that was developed by determined individual operators who required little more than the mechanical talents to produce sand, gravel and crushed stone.

Along with the consolidation taking place in the industry, an evolution also is taking place in the market. The market is no longer one in which operators compete only with other aggregates producers. Other industries are seriously looking for marketing opportunities and are introducing their industrial by-products, new products and even new materials into established construction markets. For example, recycled concrete and recycled asphalt pavements are becoming increasingly accepted materials in the marketplace.

Aggressive market development is becoming ever more critical as this evolution of industry consolidation and structure takes place. Table 9.1 summarizes the factors necessary for a successful marketing operation. These factors are considered in detail throughout this chapter.

The Marketing Tools: Marketing has been a recognized business tool in the consumer industry for many years, but has just started to gain respect in the industrial markets since the 1960s. Marketing in the aggregates industry generally has been limited to the larger and/or publicly held national firms. An assumption of equality between producers exists in the aggregates business today in the equipment available to process the aggregates and even in the raw material (aggregates) available in a given market. Production techniques often are similar because of the exchange of technical information within the industry. Credit to purchase equipment may not be the limitation it used to be now that the industry is comprised, to an important extent, of large national and international firms. All these factors, therefore, can be considered essentially constant in the equation for successful construction aggregates companies.

An important variable in the equation that determines profit is the people who manage the resources. If the managers of a company stress marketing as a key function, an important advantage can be developed over their competitors. Real opportunities exist for firms, particularly small ones that compete with aggregates companies that have become unresponsive and inflexible to customer needs.

Table 9.1 Flow Chart for Successful Marketing Operation

Problems: Sell construction aggregates in a competitive market.
Sales Solution: Be the low-priced supplier.
Marketing Solution: A commitment from top management that the marketing function is important to the success of the firm and the organization is aware of this commitment. **People** Hire qualified staff Train them Support them Commit to organizational quality **Analysis** Obtain reliable economic information Analyze the competition (products and firms) Segment the market (customers, products and geographic areas) Forecast demand **Tools of the Trade** Direct sales contact Seminars Participation in professional groups Direct mail Trade publication articles Publications Industry association resource groups **Plan (identify and set action steps)** Objectives Strategic recommendations (what needs to happen to make the plan a success) Markets and priorities Product positioning Pricing policy Promotional programs Distribution of promotional materials Forecast revenues and profitability Measurement/tracking system to be used to monitor the plan
The marketing solution is not as simple and straightforward as the sales solution, but the rewards are greater.

Many examples can be cited of aggregates companies working with local design and governmental agencies to write specifications that are technically sound and economical.

Before considering how to conduct aggregates market planning, however, it is important to understand the difference between sales and marketing. The definition of industrial sales and marketing also must be clearly comprehended.

An Analogy: The difference between marketing and sales may be compared to the difference between planting a field of wheat and harvesting the wheat. Following this analogy, a firm in the aggregates industry that fails to sow and nurture its seeds properly, or depends on someone else to plant, can look forward to meager yields in future harvests. In other words, companies that depend only on sales minimize opportunities for new market growth because they are accepting a common misconception that construction aggregates is a commodity. Relegating a product to a commodity means that price is the only factor differentiating one producer's product from another. Often, however, price is not the most important concern. If price is established as a major factor, the producers must respond to the decisions and plans made by others, which may or may not be in the best interests of the producers, decision makers or owners.

Definition of Industrial Marketing: The aggregates industry is best served by an *industrial marketing* approach rather than a consumer approach. B. Charles Ames in his article *Trappings vs. Substance in Industrial Marketing*,[1] defines industrial marketing as:

> "A total business philosophy aimed at improving profit performance by identifying the needs of each key customer group and then designing and producing a product/service package that will enable the company to serve selected groups more effectively than does its competition."

The above definition of industrial marketing points out the following important criteria involved in the marketing function:

1. Identify customer needs;
2. Develop and produce the right product/service that will serve customers more effectively than the competition;
3. Identify customer groups and products where the company can gain a competitive edge; and
4. Improve profit performance.

Industrial marketing requires the management of the company to believe that the entire firm must be marketing oriented. A marketing orientation cannot be achieved by marketing's efforts alone. *Marketing must be a basic philosophy within the company and must have the allegiances of all executives who are acutely aware of the tangible value that marketing provides.*

Marketing managers may have difficulty defending a marketing orientation because their recommendations often lack the impact of definitive technical data. The marketing department must rely on forecasts and judgment; the operations department usually is able to supply specific figures for construction and operating costs.

The management of most companies agrees with the fundamental principles of marketing, but only a few live by them. Those that incorporate fundamental marketing principles into their basic strategies will be the most successful companies in the aggregates industry of the future.

Definition of Sales Function

It has been said that marketing is good sales but sales is not marketing. In many ways, outstanding sales personnel carry out market development in conjunction with their normal activities. The sales function takes on different forms depending on the size of the company, the size of the orders and even the type of customer. There are many sales activities in the aggregates industry, but sales personnel are professional representatives who are viewed by the client as consultants and problem solvers. Sales representatives look at application problems and make proper recommendations to the client. The sales staff may:

- Supply technical information to individuals who are not well informed about products, prices or distribution;
- Quote prices to supply aggregates to various projects or large customers;
- Work with customers to solve either internal or external problems;
- Be the eyes and ears for the marketing function by keeping informed on competition, current projects and the acceptance of the firm's products in the marketplace; and
- Coordinate the supply of aggregates with customer needs through forecasting and scheduling.

The successful sales staffs in the aggregates industry wear many hats, but their greatest asset is their responsiveness to their customers' needs. This is where the previous marketing efforts turn the product/service into revenue and earnings.

The sales effort can be very rewarding because there often is a short time span between the sales call and the actual sale. Sales differ from marketing where the actual use of a product by a customer may take months or even years. Now that marketing and sales have been defined, the next step is to build these functional areas into the organizational structure of a company.

Changing Role of the Aggregates Salesperson

Salespeople are becoming marketing oriented. They are being asked to manipulate the variables of product, distribution, promotion and price to meet needs of the market. The salesperson must also help to build a profitable and continuing business for the company by maximizing pre-tax dollars over both short and long periods. In the past, the salesperson did little analysis of the needs of the customer. Now the aggregates salesperson is being asked to perform analyses pertaining to many different activities in the business. Analyses and resulting strategies in the following broadly varying areas are not atypical:

- Process specification
- Manufacturing capacity
- Analysis of competitive systems and proper selling strategies
- Production planning to produce the required quantity of finished goods
- Promotion (including merchandising, publicity, advertising and personal selling)
- Telephone call planning

- Sales training (both personally and for the sales force)
- Market segmentation
- Forecasting
- Pricing (including payment terms, classes of trade and quantity discount structure)

Equipping Salespersons to Accomplish their Job

Formal Job Description Changes: The changing face of the company in the aggregates industry is dictating changing activities normally thought of as sales duties. Following the Total Quality Management (TQM) technique, which is currently in vogue, the *voice of the customer* is considered the real manager of the company. The *voice of the customer* is broadcast throughout the company by the salespeople because they are the conduit through which the customer communicates with the organization. Consequently, the salesperson is called upon more and more to explain the customer's position to the different units inside the company. This is the real reason for the expanded role of the salesperson: customers are now the real bosses or their business is taken elsewhere.

More Analytical Work: This expanded role for the salesperson presents some very interesting challenges for the professional aggregates salesperson. Today, as in the past, the successful salesperson needs a high level of market knowledge along with a significant knowledge of the technical aspects of the product. Additionally, the organization often requires the salesperson, with very little training, to represent the customer to other functions. The team approach can often assist the salesperson in this task. Typically, a multi-functional team is formed. The contributions of the entire team result in a product that fits the capability of the organization and satisfies the customer's needs.

Increased Classroom Training: The aggregates salesperson often attend special training sessions, including the NSSGA's seminars for both entry-level and advanced salespersons and sales managers. The frequency and type of seminars have been expanded and instruction has been designed to explain and incorporate an understanding of the buying process from the customer's point of view.

Other Activities

Probably the most important consideration is the amount of *promotional activity* required of the professional aggregates salesman in today's market. The fundamental reasons have not changed for merchandising, advertising and personal selling activities. However, the importance of this area has increased from a strategic sense. Salespeople must spearhead the publicity and public relations activities of the company.

NIMBY

An important strategic issue facing all producers today is the affect of the *NIMBY* movement on the aggregates industry. *NIMBY* stands for "Not in My Back Yard" and deals with that element of society that actively advocates more restrictive regulations and zoning practices designed to reduce the number of aggregates operations in the country. In this arena, the professional salesperson should be the voice of the company to the customer and the community. *No more pressing need for quality work in the industry exists today than to promote realistic regulations and zoning practices.*

The analysis and resulting publicity and public relations strategy is normally handled by the sales persons. Their work should include the preparation of informative news releases about positive community activities undertaken by the producers. Extensive civic, club and [aggregates] association involvement should be utilized to place the company and the industry in the best possible light relative to the communities' perception of their worth. Community relations work is a formidable task that is becoming more important as the available aggregates deposits become more and more scarce.

Summary

In summary, the professional aggregates salesperson is taking on more tasks than in years past. Activities are being expanded that force interaction with other functions within the company. These complex activities increase the responsibility of the sales position because now, more than ever, the salesperson is the voice of the customer. The salesperson relays important information to the different areas of the company in a manner that can be understood by everyone. *The role of the salesperson is enhanced by viewing the buying process from the eyes of the customer.* The salesperson will continue to be more and more important to the success of the organization.

Organizational Structure for Effective Market Development

The task of shifting a company that has been strictly engineering and production oriented to one that incorporates marketing orientation is enormous. Serious effort is required on the part of marketing executives to ensure that their proposals are carefully conceived, solidly documented with market and economic facts and fully considered in terms of their impact on operating functions.

Often, reluctance exists among aggregates producing companies to consider increased expense for developing, testing and starting a new product or taking any actions to build a stronger market position if these actions cut into short-term profits. Concentration on short-term profits can cause a firm to miss key market changes and, in the end, do serious damage to the competitiveness of the company.

Ingredients for Implementing a Marketing Philosophy: Philip Kotler stated, ". . . sales orientation is product centered. The marketing approach is customer centered." He used a *marketing philosophy* in which a customer is called upon and asked, "Tell me what I can do to help you make or save money and better achieve your objectives." Someone using a sales approach might say, "I'll sell this to you at a lower price today only."[2]

The following four essential ingredients must be present for implementing a marketing philosophy:

- Commitment by top management to give marketing at least an equal status with other essential corporate functions
- Qualified personnel
- Reliable market and economic information
- Short- and long-term plans that ensure the right strategic focus for the business

No corporate function can be successful without top management's support and commitment. The rest of the organization must feel the presence of top management's support and recognize the importance of marketing to the success of the firm.

Qualified Personnel: To be an effective marketing executive in the aggregates business, a superior knowledge of the market and the economics of the business are needed, together with the ability to make good business decisions. Without these characteristics, the marketing executive cannot command the respect of other executives to induce them to follow marketing's lead.

Few ready-made individuals exist with marketing skills. No accepted set of skills exist in aggregates marketing that are readily transferrable from one situation to another. The individual needs a comprehensive understanding of the particular market as well as the economic aspects and operating characteristics of the business. Mature business judgment also is required to achieve a balance between functional considerations (i.e., product lines, production costs and selling price alternatives) and long- and short-term interests. These considerations must then be used to establish sound recommendations for achieving maximum growth in sales and earnings.

Individuals in companies that are successful in marketing come from a variety of functional backgrounds. They could have experience in finance, engineering or operations as well as sales. A foundation of knowledge and insights about the business ensures, for marketing, its role as a key function of the organization. Upgrading marketing skills and techniques always should be a primary concern in the marketing function. This is discussed later in this section under *Training for Marketing Personnel.*

Reliable Information: A company needs a systematic method to obtain information from its customers and the industry concerning:

- Feedback on its performance;
- Competitors' actions and performance; and
- New ideas.

> *Feedback on performance:* Establishing criteria to identify trends must be part of the marketing function. Marketing decisions must be based on the best available internal and external information. Generally, internal information is financially based and should

be modified to reflect what happens in the market segments, the product lines, and the company's cost and profitability situation. Balance of sales and production is a constant concern in the aggregates industry. Internal sales and production analysis identify where an unbalanced situation is occurring. An informational system of this type should be set up and regularly monitored.

Competitors' actions and performance: A thorough analysis of the competition is very important. This analysis should identify competitive firms' products and quality, financial resources, pricing policies and business strategies.

New ideas: Monitoring industry publications and attending industry trade shows can lead to the identification of new applications and products. No substitute exists for talking with customers and creating ways to use this valuable information.

Strategic Planning: Planning is essential to long-term success in the aggregates industry. If a company is to succeed as a marketing oriented entity, strategic planning is a necessity. Strategic planning is defined as planning that establishes the focus and direction of a company. Strategic planning should be a collaborative effort with all key individuals of an organization contributing their respective points of view. The key organizational personnel included in the planning process should include all senior executives of the company including the president, the chief financial officer, the production manager, sales management personnel, marketing management personnel and any other individuals uniquely qualified to contribute to the process. A balance must be maintained between organizational functions and long- and short-term interests to assure the development of a sound strategic plan. Strategic planning for aggregates companies in the future must be a key activity. Marketing's role in the strategic plan is one of communicating the market conditions and the company's ability to respond to the threats or opportunities that exist in the market.

Staffing and Training for a Marketing and Sales Orientation

Two basic types of training should be given to all sales and marketing personnel:

1. *Product knowledge and product applications:* This area includes:
   - Specified quality standards for all products as well as the quality expected for the customer's products;
   - The rates of production (tons per hour) and the various products each source is capable of producing and production balance, limitations, effect of inventory and shipping rates; and
   - Sound technical knowledge about the end use of aggregates, such as soil mechanics (geotechnical engineering) and pavement design.

2. *Art of selling:* Few individuals are naturals at selling products such as aggregates. Many people are extroverted and friendly, but being friendly is not enough. Sales personnel must be well trained in the art of selling. Appropriate training includes sales strategies, how to manage accounts and how to plan and develop the right portfolio of accounts and prospects over time.

In addition, techniques and tactics must be learned such as making presentations, closing sales, dealing with objections and managing time to the maximum potential. Some of the generally accepted methods of sales training in the aggregates industry are as follows:

- *Association sales training.* Aggregates associations, such as NSSGA, offer excellent, low cost sales training programs. Sales training can be targeted to several different levels of competency specific to the aggregates industry.
- *Local sales training.* The use of local companies that specialize in sales training can do an excellent job of teaching basic sales skills, even though they often have little knowledge of the aggregates industry.
- *In-house sales training.* Depending on the size of the company, different levels of in-house training programs can be developed by company staff.
- *Consulting firms.* Local and national sales consulting firms can tailor a program specifically for the needs of a specific company and sales staff.

Generally, sales training deals with the interaction between sales and marketing personnel and the customer. The sales person represents the company, so the best interest of the company is served if it is represented by a well-trained sales staff.

Training for Marketing Personnel

Generally, marketing personnel have a broader picture of company-wide strategy than do sales personnel. As discussed later, obtaining highly qualified people is a key ingredient in developing a successful marketing staff.

While background knowledge and education are important, continuing education and training also are necessary. Various associations and many business schools have both basic and advanced short courses, and classes covering the role of marketing in organizations. In addition, many texts and articles are available on marketing. For example, Philip Kotler's classic marketing text, *Marketing Management, Analysis, Planning and Control*[2] is an excellent reference. With the dramatic changes taking place in the aggregates industry, companies and marketing personnel are well advised to upgrade their marketing skills through continuing education and participation in industry training programs.

9.2 Market Positioning

No aggregates company can offer all products to all market segments. A conscious decision therefore must be made as to what products and services can be supplied competitively and profitably. The company must examine its strengths and opportunities and take a position in the market.

As stated by A. Ries and J. Trout, "Positioning starts with a product: a piece of merchandise, a service, a company, an institution, or even a person ... but positioning is not what you do to a product. Positioning is what you do to the mind of the prospect. That is, you position the product in the mind of the prospect." [3]

In taking a position in the market, a company helps customers know the differences in benefits between their products and services, and those of competing companies. If this is communicated effectively, the customer will perceive the aggregates supplier as best satisfying a particular need.

The steps in developing a company market position are (1) identify possible positions, (2) select a position, (3) develop that position and (4) actively promote the position chosen by the company.

Michael Porter in *Competitive Strategy* [4] and David Aaaker in *Strategic Market Management* [5] suggest that there are three generic strategies in market positioning:

1. *Low cost provider.* In the aggregates business, this may come from the ability to keep labor costs low, locate in a way that minimizes transportation costs or keep costs low through automation and production process innovations.
2. *Differentiation.* Be unique in some respect as compared with the competition.
3. *Focus.* Target a particular customer segment or region, and within that segment pursue either a differentiation or low cost provider approach. The focus approach usually best describes the construction aggregates market.

In addition to company positioning, products may be positioned in specific market segments. Market segmentation positioning depends largely on the target markets and the competition. Market segmentation is considered in more detail later.

When properly communicated, a company's market position should be understood by the customers in such a way that they know the differences between the firm and its competitors. Based on their requirements, the customers then select the firms that are perceived to offer the best value.

Market Analysis

Successful market positioning cannot be accomplished without a thorough analysis of the company's strengths and weaknesses as well as those of the competition. Consideration also should be given to the strengths and weaknesses of specific competing products. A checklist for developing a market analysis is as follows:

1. *Define the company's business*. For example, "The company is in the business of providing construction aggregates, transportation and technical support in the Lincoln County market."

2. *Analyze the markets being considered*. Look at market growth and the share of the market held by the company and major competitors.
3. *Identify specific significant actions* that give evidence that the market positioning is successful, such as total volume, average sales prices and competitors' reactions.
4. *List some of the significant advantages and disadvantages* the company has that differentiates it from the competition. From this list, the company can build on the advantages and work to neutralize or eliminate the disadvantages.
5. *Develop a market profile* that identifies all segments on which the company wants to focus.
6. *Develop a benefit analysis* by decision maker units (DMUs), such as contractors, specifiers, owners, etc. Rank how the DMUs value the various criteria, price, quality, delivery, service.
7. *Conduct a competitive analysis* of how the company compares in terms of various criteria (price, quality and technical service) and rank each of the criterion as better, equal or worse than the competition.
8. *Identify the strength of competitors* by segments (by either product or location) of the market.
9. *Identify the competitive positioning in the market*. This can be done by market segment: low service-low cost, high service-high cost and specialty market versus full product line.
10. *Identify the buyer's purchase process*. Who makes the final decision? Who influences the buyer and how?

The checklist above requires a thorough knowledge of the market. Unless an analysis of this type is performed, an aggregates company cannot effectively position itself in a market.

The use of a matrix is an excellent way to better analyze competitive producers and products. The matrix compares the competitors or their products to significant criteria in the market place, as illustrated in Table 9.2.

From the matrix analysis given in Table 9.2, the producer can conclude the following:

Price: The producer is competitive in the market except for competitors A and E.

Delivery: The producer has the same or better delivery capability than the competitors in the market except for competitor B.

Quality: The producer is equal to the competitors except for competitor C.

Technical Support: The producer has a stronger technical support system than the competition except for competitor B.

Location: For a particular project or customer, the producer has a better or equal location from a transportation standpoint than all competitors except competitor D.

Table 9.2 indicates that four of the five competitors emphasize technical support. A sophisticated company determines how important a certain level of technical support is to customers, and whether or not it will make a difference in their decision. Other items that can be included in this type of matrix are the relative size and market position of the competition.

Table 9.2 Example of a Matrix Analysis of Competitors

Competitor	Price	Delivery	Quality	Technical Support	Location
A	Worse	Even	Even	Better	Better
B	Even	Worse	Even	Worse	Better
C	Better	Better	Worse	Better	Even
D	Better	Even	Even	Better	Worse
E	Worse	Better	Even	Better	Better

Worst = Producer is worse than competitor.
Even = Producer is equal to competitor.
Better = Producer is better than competitor.

Since the construction aggregates market usually is quite localized due to transportation costs as a ratio of total delivered costs, it is doubtful that a producer will have a large number of competitors. Therefore, the producer's opportunities should be relatively easy to identify and point out to prospective customers.

Matrix for Comparing Product Lines: A similar matrix should be used for evaluating products. An example of an analysis of competing aggregates products is given in Table 9.3.

This type of matrix analysis can be used for a producer's entire line of products. The primary purpose of a matrix analysis is to help identify specific product strengths and weaknesses.

Table 9.3 Example of Matrix Analysis for Competing Base Products

Aggregates Base Materials	Price	Availability	Structural Strength	Uniformity
Crushed Stone	Medium	Yes	High	High
Sand and Gravel	Low	Yes	Med-Low	Medium
Asphalt Base	High	Yes	High	High
Recycled Concrete	Low	Yes	Med-Low	Med-Low
Lime Treated	Med-High	Yes	Medium	Medium

Additional Tools for Market Analysis or Market Research: Customer surveys, market needs analyses and corporate image assessments are quite valuable and are performed in various ways. Typical tools used by outside consultants are telephone interviews, personal interviews, written questionnaires and focus groups.

1. *Telephone interviews and written questionnaires.* This method can target specific decision makers and identify their needs. Telephone interviews and questionnaires also can provide feedback on the decision makers level of satisfaction. The credibility of this type of survey depends largely on the expertise of the people conducting the survey and the level of input producers have in the development of the questionnaires.

2. *Focus group interviews.* Focus group interviews are meetings of small groups, randomly selected from a target audience, with certain interests in common. Normally, a focus group consists of approximately eight to 12 people. The interview itself lasts from one to 1-½ hours. During the interview, participants discuss topics presented by a moderator. Ideally, the moderator is someone unknown to the participants. The goal of a focus group interview is to obtain information that is truly reflective of the participants' feelings and perceptions. Due to the group dynamics involved in focus group interviews, information becomes available that might not emerge in conventional methods of interviews.

Some examples of focus group key questions are as follows:

1. Thinking back to the last time you used this product, what were the factors that prompted its use?
2. If you wanted to find out something about the product, where or to whom would you go?
3. When purchasing a product, how do you judge its quality?
4. What do you know about the product's standards in your state?

From a summary of the responses to questions of the type presented above, a producer can develop a substantive promotion program tailored to factors considered by the customer as key decision points.

In many respects, market analysis is the foundation to the entire planning structure. If the foundation is not sound, there is little chance that the planning structure will give the desired results.

Market Segmentation: Markets consist of buyers that differ in one or more respects. Differences include needs, resources, geographical locations, buying attitudes and buying practices. Any of these variables can be used to segment a market.

Once an appropriate market segmentation has been developed, it becomes a powerful tool for targeting particular customers. Segmentation allows the producer to use the focus strategy to better provide products and support that appeal to a particularly suitable segment.

Major segmentation variables for construction aggregates markets are as follows:

1. Type of buyer:
   - Retail, home owner, do-it-yourselfer
   - Small contractor (buys less than $5,000 per year)
   - Medium-sized contractor (buys from $5,000 to $50,000 per year)
   - Large contractor (buys more than $50,000 per year)
   - Governmental contracts (city, county, state and federal)
   - Manufacturer. The manufacturer uses, for example, the aggregates to produce concrete pipe, concrete block, ready-mixed concrete, asphalt concrete or specialty products

2. Geographical areas:
   - Located within certain governmental boundaries
   - Located within a certain distance or travel time from the production facility
   - Located within certain sales territories

3. Types of decision maker units:
   - Contractors
   - Specification writers
   - Owners
   - Government agencies

4. Product lines:
   - Concrete sand used in ready-mixed concrete
   - Crushed stone such as ASTM No. 7 size stone (¾-inch top size down to No. 4 sieve size) which is used, for example, in asphalt paving aggregates
   - Gravel such as ASTM No. 4 size stone (2-inch top size down to ⅜-inch sieve size), which is used, for example, as pipe bedding for water and sanitary sewer lines
   - Specialty aggregates such as products that are utilized in exposed concrete applications
   - Customer size:
     a. Top 20 customers overall in tons or dollars
     b. Top 20 customers in each product line in tons or dollars

Many ways exist to segment markets. For meaningful results, however, the market segments should have the following characteristics:

- Be measurable by size and purchasing power
- Be sustainable with size and/or profitability large enough to be meaningful for future continuity
- Be accessible and reachable
- Provide useful information to the producer. Little reason exists to collect the segmentation data if there is not a sound application for the information.

Segmentation is a useful tool to understand better the markets so positive actions can be taken for market forecasting and planning.

Market Forecasting: Few areas in the aggregates industry have more impact on the budgeting process than forecasting. The entire budgeting process begins with the sales forecast. This forecast establishes production levels that determine operating costs and cash requirements for receivables and product inventories. All these functions are important to the profitability of the aggregates firm.

A market demand forecast is based on the prevailing economic condition in an area that may be relatively dynamic during a given budget period. The market demand for construction aggregates is closely tied to the economic conditions of the construction industry as reflected by the construction contracts let in the firm's market area.

Aggregates plant operating costs depend on the balance between production levels and plant capabilities. Proper product mix and production levels are critical to maintaining low costs. Low costs determine how competitive and profitable a firm is in the marketplace.

Due to the wide range of uncontrollable variables, forecasting is never completely reliable. Some of the tools that are effectively used in the forecasting process to improve accuracy are the following:

1. U.S. Geological Survey–Mineral Industry Surveys.[6] These surveys come out quarterly and list the quantity and value of crushed stone and sand and gravel used by state. Aggregates producers assist the USGS in these surveys by responding to the USGS requests for production reports.
2. F. W. Dodge Reports.[7] Some of the services offered by F.W. Dodge that can aid aggregates producers in forecasting.
3. State Highway Agency Plans. Most state transportation agencies have five-year plans for construction projects. Many other governmental agencies also develop budgets that include construction projects in the planning stage. Estimated volumes of aggregates can be determined from plans and proposals.
4. State Aggregates Producers' Associations. Some state aggregates producers' associations develop historic aggregates usage volumes in conjunction with dues collection. This information can be used to estimate market share for a certain geographic area.
5. Housing Associations. The National Housing Association and local housing associations can furnish information on trends and forecasts of home building activities. In evaluating this data, a lead-time of up to six months exists between the securing of a building permit and the time actual aggregates is used in housing project.

The forecast process starts when top management examines the company's opportunities and requirements and sets corporate goals for the year. Normally, deadline dates are set for preliminary review of the forecast followed by additional reviews, as necessary, before the final review. Major items to be considered in developing a forecast are the following:

- Contacts with major customers and decision makers to obtain their opinions on future demand. This information can give insight into what projects are coming in the future and what projects or customers may be altering their level of activity.
- Customers' past usage of aggregates. This information should be reviewed for a three- to five-year period. The data are most helpful from steady customers who manufacture products from the company's aggregates.

Various levels of sophistication are used for forecasting in the aggregates industry. The level selected generally is related to the size of the producer and the priority it places on forecasting. A sales forecast for a small producer might be determined entirely from a conversation between sales and production personnel. In larger firms, sales personnel may enter sales forecasts into computers that cumulate various products into monthly sales volumes (in terms of quantities and revenue) and make the information available to production planners.

Once a total market area demand is forecast and an estimate of an individual firm's market share is made, the producer can forecast its total product shipments. This estimate is further reduced to individual aggregates size forecasts. Other important aspects include the timing of sales and the average sales price for each product.

Inventory Controls: Inventory planning is critical to an aggregates company's profitability. Storing aggregates in inventory is like storing dollar bills in a warehouse. Even if the money used to produce the aggregates stockpiles does not have to be borrowed, it could be drawing interest. If the money has to be borrowed, then the company is paying interest for stockpiled materials.

Achieving a proper balance between too much or too little inventory is the responsibility of the sales, marketing and production personnel. They must satisfy all their customer's needs by having the right products available in the right quantity at the right time. Inadequate inventory can delay a customer's project, which increases its cost and causes considerable ill feelings toward the aggregates producer. The aggregates company may have to work overtime to try to reduce the customer's lost time and these increases operating costs. On the other hand, if the inventories become too large and are carried for too long, the company is faced with unnecessary interest expense. *The joint effort of sales, marketing and production personnel cannot be over-emphasized in the area of inventory control.*

9.3 Quality Organization and Quality Products – A Competitive Edge

Real quality in the aggregates business means that top management takes the leadership to assure that high standards exist in everything the company does—from answering the telephone to producing aggregates. Quality should be a corporate philosophy backed with genuine top management commitment.

A definite strategy must exist to instill quality in an organization. *Strategic planning helps the firm do the right thing. Quality strategy means that the firm does things right. Total strategy means that the firm does the right things right.*

When one considers why customers quit doing business with a supplier, the importance of a quality organization becomes apparent. Surveys that address the issues of why customers discontinue business with their suppliers indicate:

- 14 percent leave because of product dissatisfaction;
- 68 percent leave because of the attitude and indifference of the supplier's employees; and
- 18 percent miscellaneous.

It makes sense to correct the problems that result in the highest percentage of customer dissatisfaction. To achieve this, *the major focus must be on satisfying the customer 100 percent of the time.* This means that products meet specifications, invoices are prompt and accurate, scale and load out personnel are courteous, knowledgeable and well trained, deliveries arrive when promised and problems are handled in a prompt and satisfactory manner. These are just a few of the functional steps that can affect an aggregates customer. These functions need to be reviewed constantly and improved.

A successful sales effort requires knowledge not only of product specifications but also of the customer's requirements. Typical aggregates gradation specifications permit a tolerance of plus or minus 4 percent. In contrast, the gradation specification for asphalt concrete may be plus or minus 2 percent. This means that an asphalt concrete producer with plus or minus 2 percent gradation tolerance will experience considerable specification problems using aggregates from a supplier who is producing aggregates with a tolerance of plus or minus 4 percent. Customers therefore expect their aggregates supplier to furnish materials that are not only within specifications, but also consistent with specific needs.

Increasingly, the level of service provided is becoming a factor that distinguishes between aggregates producers. Many aggregates companies now perform customer satisfaction studies. Such studies identify each customer's expectations for each product and the producer's related services, and how the producer performs when compared with competitors. A survey also identifies what is most important for customers and where the company can obtain the highest return for improving its service and products.

How Much Does Quality Cost?

Quality is defined as "the degree of excellence which a thing possesses." This definition leaves open the possibility that a given object may be judged as having either good or bad quality.

Extra Effort: In aggregates production, the desire of all producers, as well as of their customers, is that the product has a high quality. Obviously, this requires diligence on the part of the producer to assure that clean, unweathered material is selected for processing, that production rates are appropriate to permit uniform crushing and screening to occur, and that careful handling of finished product prevents segregation. These procedures must be monitored constantly and require extra effort. These efforts are an integral part of producing aggregates and should not be viewed as causing extra costs that make the product in any way unnecessarily expensive. Attention to the quality of a product merely provides assurance to the producer that his product is saleable and to his customer that it is usable and will perform as anticipated.

Any costs associated with assurance of aggregates quality are far outweighed by costs associated with not providing quality. Severe penalties can be assessed against material producers when their products fail inspection and require costly replacement to enable acceptance of construction projects. Even greater penalties can occur when low quality materials are incorporated into structures that later fail while in service. Litigation ensuing from such events can make quality control costs seem minimal indeed.

Many producers have lost customers because of failure to supply a quality product. They experience a financial loss because of reduced sales, and in most instances expend considerable effort and money attempting to regain those lost customers. Experience has shown that it is better and less costly to provide quality on the first effort.

Product quality must start with the people who produce the material. The labor force must be an important part of the team. They must know the requirements expected by the customer and must be trained to perform and favorably interact with the customer.

The Japanese labor force has after work clubs to study different ways to produce a better product and reduce costs of production.[8, 9] This practice is not currently part of the American culture, but management must consider this approach to quality in the future.

How much does quality cost? Until top management develops a budget item for quality, its true cost will never be known.

The Quality Process

Quality Comes From People and Attitudes: Leadership must set the example in encouraging quality. A clear set of guidelines should exist for establishing quality. To be effective, quality guidelines must allow employees to both understand and want to act in ways that promote quality. This often includes internal programs to communicate evidence of top management commitment to quality, the reasons for emphasis on quality, and what the importance of quality means to the future of each individual's job. A sequence for developing a quality process is as follows:

1. An audit of product line and job function quality should be taken at least on an annual basis. A large project should be broken down into smaller and more manageable sizes.
2. The entire organization should be made aware of the emphasis being placed on quality.
3. Teams must be developed to work on specific products or function areas that have been identified by the audit.
4. Suppliers of equipment and critical materials need to be brought into the quality improvement program. Little chance exists for meeting quality standards if suppliers are not playing by the same rules.
5. Methods for measurement of quality must be established and monitored to assure that progress is being made toward the objectives set.
6. Every important customer should be surveyed after every job to determine whether the customer's expectations for quality were met and exceeded.

Resources for Quality Improvement

W. E. Deming is considered the father of the Japanese quality improvement revolution. The Deming cycle is a concept of a continuously rotating wheel used to emphasize the constant interaction among research, design, production and sales in order to arrive at improved quality that satisfies customers.[8] Phil Crosby's book, *Quality is Free*[10] gives good insight into product testing. The Minnesota Mining Co. (3M Co.) uses a program called "Total Quality"[11] that is applicable to the aggregates industry. The 3M Co. promotes the philosophy that change is always taking place. Through education, training and planning a firm can survive the changes that are and will continue to take place. Many individuals and firms offer services in the area of quality; each has a unique approach to the subject. An aggregates company interested in quality improvement should find one that fits its needs and objectives.

Monitoring Other Research Programs by the Aggregates Industry: Some of the most extensive research now being conducted is in the area of highway construction. The Strategic Highway Research Program (SHRP) is a $150-million research program being undertaken by the federal government through the Federal Highway Administration, the National Research Council, and the American Association of State Highway and Transportation Officials. The SHRP program will have far-reaching impact on the aggregates products used in highway construction for many years. This research and other studies must be monitored closely by aggregates producers. Whenever possible, producers should encourage the sponsoring agencies to include their products in the research projects. Once a producer's product has been successfully used in a research project there is a good chance the product will be specified in future projects.

Each state transportation agency also conducts materials research. The results of these programs lead to changes in specifications, which can have a significant impact on aggregates producers. Therefore, producers must be aware of the research projects in progress or in the planning stage. Whenever possible, they should cooperate with the agencies conducting these projects by providing technical input, materials and by monitoring the results.

Some states are going to end-result specifications, which means that the aggregates is not checked for compliance with project specifications before being used on a project. After the aggregates are in place, tests are performed to determine if project specifications are satisfied. End-product specifications place additional pressure on aggregates producers to supply products that meet specifications at the plant and on the project. If the product does not comply with the specification for the project, the product or the mixture containing the product will be rejected and must be replaced. In some cases, the producer has no authority over the handling or placing of the materials, but often is still responsible for meeting the specifications after placement.

Participation and monitoring by aggregates producers of local, state and national research helps the producers know what products will be needed in the future. The small cost for doing this has the potential for significant long-term benefits. Actual involvement in a research program often is encouraged by the research agency to be able to consider the producers' input on specifications and costs.

9.4 Product Development and Product Promotion

Few areas in the aggregates industry offer greater opportunities for increased sales and profits than the marketing functions of product development and product promotion. According to Philip Kotler in *Marketing Management, Analysis, Planning and Control,*[2] the product development and promotion process can be broken into the following eight stages: idea generation, screening, concept development and testing, marketing strategy, business analysis, product development, market testing and commercialization. Few products survive through this process from the initial generation of an idea to the marketing stage. However, the financial rewards can be enormous for the successful developer of a new product.

Product promotion is the act of taking an existing product or service and through education, advertising or other methods creating a new, perceived value of the product by the decision maker. Once the decision maker is convinced, the product or service is superior in performance and/or cost to the current product, a switch is made to the product being promoted.

Changing Markets

Construction aggregates markets are constantly changing. New producers enter the market at the same time existing producers leave or change ownership. Existing products may be replaced by new products. Specification changes impact products and production costs. An evolution is presently taking place in the aggregates market that will continue far into the future. A partial list of *threats or competitive factors* given in a National Stone, Sand & Gravel Association publication[12] identifies a number of changes presently taking place in the market:

- Customers and public agencies are asking for higher quality products than in the past.
- Historic aggregates markets, such as aggregates base, are leveling off or decreasing as more highway construction dollars are used in maintenance and less for new construction.
- Open graded aggregates base materials are becoming more common.
- Hot mix asphalt concrete base is declining in most markets.
- Recycled asphalt and portland cement concrete have gained acceptance in some markets.
- Skid resistance of the asphalt concrete surface is an important factor in highway safety.
- Manufactured stone sand is being employed in many asphalt and portland cement concrete applications.
- Control of erosion is requiring more riprap and filter materials. Construction of storm water settling basins is common in urban development projects.
- Markets must be found for aggregates by-products to reduce stockpiles of products that have little or no value. The sale of these products could reduce the unit cost of production and have a major influence on revenues.
- Transportation costs are increasing due to highway congestion. However, off peak (night) delivery is being considered to reduce costs and inconvenience to the traveling public.

This list summarizes just a few of the changes taking place in all markets of the aggregates producer. Only by developing market plans and constantly updating them can a producer be aware of the market changes and respond in a timely manner to them.

The Changing Role of Sales Personnel

The image and activities of sales personnel are changing in the aggregates industry. Some sales personnel will continue to take sales orders, but these people are gradually being replaced by *customer service functions* and dispatchers. The customer service person not only takes sales orders but also has product knowledge and understands most or all of the services a particular customer receives from the aggregates producer. The sales personnel who are needed today and in the future for the small and mid-size aggregates firms must be sources of knowledge. They will serve as *technical consultants* who solve the problems of customers and search out applications for new products and ideas.

In the future, the sales and marketing personnel must be better trained than in the past. Sales and marketing personnel will need to be teachers to present the ideas being sold properly. A technical background will be required to understand the geologic and technical characteristics of aggregates that affect its performance. This knowledge will create more value in an aggregates company's product, which can aid in increased tonnage and profits. Sales personnel also will require an understanding of the aggregates business and the delicate balance needed between sales and production to help create revenue and a profit.

As always, the sales personnel must have a competitive spirit with the intense desire to *close the sale*. An extra effort must be put forth to use creative approaches and convince the customer that the product and company being sold offer the best value for the particular application or project.

If this new role of sales personnel is to be developed, extensive training will be required. Both management and the sales personnel must have an appreciation that sales and marketing are key functions leading to the success of the firm.

The Decision Makers — Who Are They?

Each market area has its own groups of decision makers. They may be unique to each market, but several general categories of decision makers are as follows:

Architects: Architects design public and private buildings. They have many options available in construction materials for their projects. If the architect can be convinced that a certain aggregates is the best value or satisfies a particular appearance need, it will be specified for the project. *Architects are most sensitive to product quality and appearance. They may be somewhat less sensitive to price and service.*

Contractors: Contractors construct buildings, highways, dams, locks and other projects. Although project specifications usually are predetermined, some latitude exists concerning what products have the best value. Contractors can propose value engineering to an owner that consists of a revised design, which reduces the project cost or improves performance. A value engineering proposal, if accepted by the owner, can entirely change the project specifications. *Of all the decision makers, contractors are the most price and service sensitive.*

Landscape Architects: Landscape architects are using increasing quantities of aggregates and concrete masonry products to provide a natural appearance of structures and open space. *They are interested in unique shapes and colors of aggregates that are available and are less price sensitive than the contractor building the project is.*

Government Agencies: Government agencies write specifications for construction aggregates and call for public bids for the materials or for the projects that include the materials. Government agencies respond to suggested modification in these specifications but usually are more responsive to aggregates associations than to individual suppliers. They frequently are prevented by law from having single sources of supply.

Government agencies generally are building this country's infrastructure and require some of the highest quality aggregates for long-term performance. *Public bidding results in price being a significant factor.*

The list of decision makers goes on and on. Many opportunities exist to influence decision makers from the inception of the idea for a project through its design stage and even during construction. Early input and careful follow-through by sales personnel increases the marketability of a specified product. The effort spent early in a project may not yield tangible benefits for months and possibly even years. Such early effort often is not appreciated by upper management, but that attitude is changing in the more progressive firms.

Influencing Decision Makers

No substitute exists for direct contact with decision makers. Direct contact is also the most expensive and most time consuming, for both the decision maker and the producer. Many less expensive tools also are available to assist producers in influencing decision makers. These tools should be evaluated, and those that appear to be the most effective should be included in the action plan portion of the firm's marketing plan. Some of these tools available to influence decision makers are presented below.

Seminars: A technical seminar on particular construction or product subjects is an effective technique to educate and influence decision makers. Generally, this works best in groups of five to 10 where a subject of particular interest is presented for one or two hours. Seminars can even take place over the lunch hour in the firm's office. It is important to have an understanding of the decision makers: what type work they specialize in, who makes the final decisions and the normal practice followed in specifying aggregates. Visual presentations should be well organized with slides, overheads, videos and handouts of reference materials. The seminar is a teaching situation; the presenter must have all the knowledge and tools required of any good teacher.

Time for a question and answer period enhances the learning experience for the decision maker as well as the presenter.

The most expensive portion of the seminar is the time that the decision makers take away from their main work. Therefore, the seminar topics and presentation need to be practical and of interest to the participants.

Participation in Professional Groups: Involvement in professional groups gives an aggregates producer an opportunity to become personally acquainted with the decision makers as they work together on committees and attend meetings. Some beneficial groups are as follows:

- American Institute of Architects (AIA), including its local chapters
- Construction Specifications Institute (CSI)
- Consulting Engineer Council (CEC)
- National Society of Professional Engineers (NSPE)
- American Society of Civil Engineers (ASCE)
- Association of General Contractors (AGC)
- American Public Works Association (APWA)
- Society for Mining, Metallurgy & Exploration (SME)

Quite often, these professional groups have local or national conventions where producers can exhibit their products and speak with decision makers attending the convention.

Presentations at meetings or participation on panels involving a particular subject or product also are excellent methods to become acquainted with active and knowledgeable decision makers. These technical meetings have presentations on subjects of current interest. Individuals with knowledge of their products and application to the group's industry are usually welcomed to speak at these meetings.

Direct Mail: Direct mailing generally takes the least time and expense. The information, however, must be of interest and consequently should influence the decision maker. Mailing lists must be current and directed to individuals who actually make the decisions. These decision makers should include current customers, potential customers and any other group of decision makers the firm wants to influence. The list also can include suppliers and employees of the aggregates producer who should have knowledge of what the producer is attempting to accomplish in the market.

Trade Journals: The commercial trade journal approach to influencing decision makers is not very good, from a general advertising standpoint. Trade journals are, however, an excellent media to present articles describing interesting projects or product applications. An article published in a journal is considerably more credible than one published by an aggregates producer. Once the article has been printed, the publisher generally welcomes reprinting of the article that can then be mailed directly to key decision makers.

Public Relations: This area includes communication with the news media, the community, employees and decision makers. Small- to mid-size aggregates companies can obtain good value from the expense of hiring a public relations (PR) firm. PR firms have good contacts with the news media and deliver news to the right individual to ensure publication. They also can assist in developing advertisements, brochures and videos.

One individual within an aggregates company should be responsible for seeing that appropriate publicity is obtained for events and projects that are newsworthy. This person should develop press releases for distribution to radio, television and newspapers.

Social Media: The introduction of social media allows sales people to make connections with various target audiences via tools like Facebook, Twitter® and other collaborative methods. Social media can be used to learn about a prospect, share ideas with a contact or investigate a target customer's company.

Other Tools to Influence Decision Makers: Other tools available to influence decision makers include field trips to projects or production plants and presentations to college classes.

Industry Association Resource Groups

Many related industry association groups are working to influence decision makers to use their services or products. Sometimes these associations are working to influence the same decision maker to use the product or service supplied by an aggregates producer. At other times, they may be working in opposition to aggregates producers. Each of the industries is trying to promote the use of their product or service. Wise sales personnel make use of all positive technical information that can influence the decision to be made in their favor. Often excellent technical information is available to the aggregates producers, which can be used to influence decision makers from the following associations:

- National Stone, Sand & Gravel Association, www.nssga.org
- Portland Cement Association, www.cement.com
- National Asphalt Pavement Association, www.asphaltpavement.com
- National Concrete Masonry Association, www.ncma.org
- National Ready Mixed Concrete Association, www.nrmca.org
- The Asphalt Institute, www.asphaltinstitute.org.
- The Construction Specifications Institute, www.csinet.org
- American Road and Transportation Builders Association, www.artba.com
- Local state aggregates, ready-mix concrete and asphalt associations

More sources of information are readily available that can be used effectively. This is why a well conceived and executed marketing plan is so critical. Anyone interested in advising decision makers, developing a sales and marketing organization, or just trying to obtain maximum sales revenue from their aggregates firm should refer to Section 9.6 titled *Developing a Market Plan*.

9.5 Pricing of Construction Aggregates

Pricing aggregates is a complex process because the price at which a company agrees to sell its product involves considering costs (both fixed and variable), desired return on the company's investment, market conditions, competition and can even involve emotional decisions. The price of aggregates can lead to a sale that produces revenue, influences a company's market share and affects the profits of a company either positively or negatively.

Whenever customers ask about price, what they are really asking about is *value*. The customer wants to receive a fair value for the money spent. Customers will buy the product if they are convinced it is a good value. Every characteristic of the product or services provided has some (usually unconscious) value in the customer's mind. It is hard and often impractical in the aggregates business to add a desired physical feature to a product. However, a company can differentiate on some of the product characteristics (like quality and product line) or on the support services provided to the customer such as technical support and prompt delivery. Because these services add value, many customers choose the company that provides special services or product features.

To provide value, a company must either be able to do so for less cost than its competitors, or else have customers who are willing to pay extra for this value. People choose to shop at convenience stores because they are convenient. These stores cost more, but it is worth it to the customers who seek convenience. *The laws of economics say that customers are willing to pay more to secure additional value.* This means they will pay more if the product characteristics or service are truly important to them.

The subject of sales and market training is discussed in Section 9.1 of this chapter. The purpose of this training is to assure that the subject of price is the last issue discussed in a sales presentation. Contrary to what is commonly thought, price is not the first thing all buyers consider in their decision-making process. *Many sales of aggregates are won or lost for reasons other than price.* Most sales personnel, however, will cite price as the reason for lost business. Price is the most tangible and quantifiable variable but often not the most important.

One of the unique features of the aggregates business is that the product line is not very large. Generally, aggregates are differentiated by size. Usually an aggregates producer does not have more than 10 different products in inventory. Because of this limited number of products, the pricing process is simplified.

Elastic and Inelastic Markets: Aggregates pricing differs from the pricing of typical consumer products. Features can be added to consumer products to justify higher prices, such as washing machines that have different numbers of washing cycles and levels of quality. Another difference between the general consumer market and the aggregates market is that the aggregates market tends to be price *inelastic*.

Antitrust and How it Applies to Pricing of Aggregates

Few areas need greater explanation than antitrust laws. Basically, prices of products from a given source have to be equal to all buyers in the same business, and discussion of prices with competitors is not permitted. Extensive legal decisions on this subject have been rendered. Unfair pricing policies cannot be tolerated at any level of the selling process.

All sales personnel and individuals involved with pricing must review, at least on an annual basis, relevant antitrust laws. Top management should issue a policy stating its position regarding the antitrust laws. The seriousness of violation of antitrust laws cannot be overemphasized and should be thoroughly understood by all personnel involved in pricing, quoting of prices, and management of these function areas. As an example, the National Stone, Sand & Gravel Association's Board of Directors adopted a policy concerning antitrust which reads as follows:

NSSGA Policy Concerning Antitrust Compliance Policies and Procedures

The NSSGA is committed to full compliance with the letter and spirit of federal and state antitrust and trade regulation laws, as stated in Article IX of the Association's Bylaws. The Association, its Officers, Directors, Staff and Members shall, at all times, avoid discussions and actions which may be construed in any way to restrict competition.

Through its seminars, educational courses, publications, Committee meetings and other activities, the Association brings together representatives of competitors throughout the industry. The subject matters of Association activities are normally technical or educational in nature. The Board of Directors nevertheless recognizes the remote possibility that the Association and its activities can be abused and be seen by those ignorant of or determined to violate the law as providing an opportunity for anticompetitive conduct. No effort or intent to restrain competition or violate our laws can or should be tolerated. The Board, through this statement of policy, states its unequivocal support for the policy of competition served by the antitrust laws and uncompromising intent as individual companies and as an Association to comply strictly in all respects with those laws governing competitive activities.

All meetings of the Association, whether membership, Board, Committee or of any other type, shall be conducted in accordance with this Policy and the attached Checklist for NSSGA meetings. Meetings shall be conducted as though they were open to the public. All meetings shall be held pursuant to advance notice and written agenda. In informal discussions at the site of an Association meeting, all Members are expected to observe the same standards of conduct as are required by this Association Antitrust Policy Statement. Informal rump sessions called to discuss competitively sensitive issues are never permitted.

It is a violation of the antitrust laws to agree not to compete. Therefore, discussions about dividing territories or customers or limiting the nature of business carried on or products sold are not permitted. Similarly, discussions or sharing information of current prices, current price levels, or current price trends are prohibited. And, no discussion is permitted of any element of a company's operations which might influence price such as (a) costs of operations, supplies, labor or services, (b) allowances or discounts, (c) terms of sale, including credit and warranty arrangements, (d) profit margins and mark ups, and (e) capacity reductions or expansions, or production quotas or other limitations on either the timing, costs or volume of production.

Boycotts in any form are unlawful. Consequently, any discussion — no matter how fleeting — about blacklisting or circulating unfavorable reports about particular companies, including their financial situation, is prohibited. Nor shall there be any discussion which might be construed as an attempt to prevent any person or business entity from gaining access to any market or customer for goods or services, or to prevent any business entity from obtaining a supply of goods or otherwise purchasing goods or services freely in the market.

Participants at all Association-sponsored meetings are reminded that they are not bound by opinions expressed or conclusions reached at those meetings. Nor is any Member bound to conduct its business in accordance with any Association policy or proposed practice if such policy or practice might, in any way, be construed as adversely affecting competition. Speakers at Association meetings shall be informed of the need to comply with the Association's antitrust policy in the preparation and presentation of their talks.

Association policy requires that minutes of each meeting be prepared by a duly designated recorder and circulated to all Members in attendance following the meetings. Legal Counsel shall review draft minutes whenever deemed prudent by Association Staff Association policy does not require the attendance of legal Counsel at Association meetings other than those of the Board and the general membership. However, when legal Counsel is not in attendance, Association Staff are required to be present to assure strict compliance with Association policies and to consult legal Counsel as may be required.

When discussion borders on an area of antitrust sensitivity, the Association's representative in attendance shall request that the discussion be immediately stopped and, in the unlikely event that it does not, terminate the meeting and report that fact immediately to the Association's President. The matter can then be reviewed with legal Counsel and a determination made as to the necessity of further action by the Association.

The leadership of the aggregates industry, through the adoption of the above policy, shows the seriousness of antitrust laws. Based on the language in the resolution and the intent of the members of the NSSGA, no misunderstanding should exist about how individuals must conduct themselves on matters involving pricing and marketing activities.

Some Considerations Used to Develop Prices

Prices for specific products must be established at levels sufficiently high to meet company needs for overhead, operating and sales expenses and for a reasonable profit. The following factors must be considered:

- Costs
- Desired return
- Volume needed
- Market conditions
- Competition
- Corporate strategy

Cost Method for Arriving at the Selling Price

The price of aggregates is often determined by the amount of business that is available and the level of competitive firms interested in the same business. Generally, a company should establish a price below which they will not go based on cost of production, sales expense and a fair return for effort and risk. In some cases, aggregates companies also add transportation cost as an option to the buyer. In many instances, a portion of the transportation costs may even be absorbed by an aggregates producer to compensate for the transportation advantage a competitor may have to a particular project.

Types of Costs: *Fixed and variable costs* are the major inputs used to arrive at a price. *Fixed costs* do not vary with production or sales revenue. They include real estate taxes, insurance, executive salaries, rent, depreciation, etc., and are present even if no production occurs.

Variable costs on a per-ton basis change inversely with the level of production. *Variable costs* include those of labor and associated fringe benefits, fuel and supplies such as parts, electricity and explosives in the case of quarry operations.

Total cost is composed of fixed and variable costs. Ideally, an aggregates company's price, as a minimum, should recover total cost plus a profit margin. A situation may exist where a company will consider recovering variable costs and part of fixed costs. In general, this is not a wise practice, but under certain conditions may improve the long-term profitability of the firm. Examples of this approach include attracting new customers or when bidding on a large project.

Costs are affected by the level of production. If a production plant has lower than capacity sales and production, the variable costs are relatively uniform. However, spreading the fixed costs over lower than expected production results in higher fixed costs per ton of aggregates and therefore higher total costs per ton. The reverse is true for a production plant that is operated at levels above its designed capacity. The fixed costs per ton are lowered because of the high volume available to divide into the fixed costs. The variable costs per ton also increase because of the overtime labor expense, possible poor utilization of labor and excessive maintenance. Figure 9.1 shows the sales volume of aggregates required for a particular operation to break even (A) and produce a profit (B).

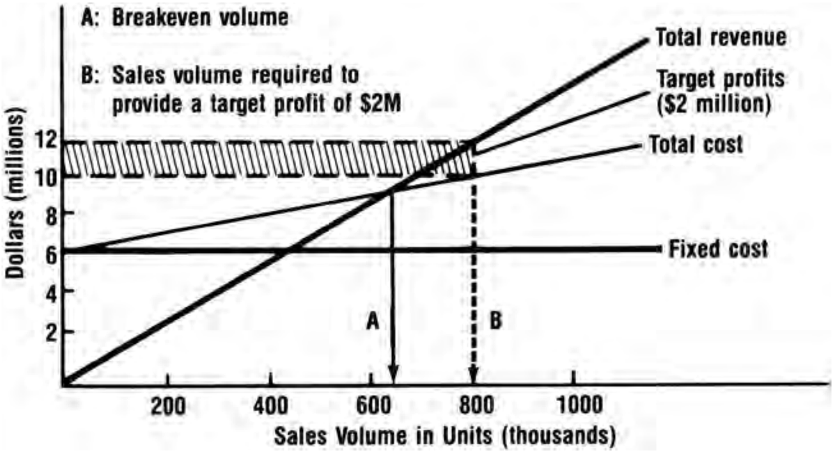

Figure 9.1 Sales volume required to exceed costs and produce a profit for a particular aggregates operation.

Market Segmentation Pricing

One of the values of *market segmentation is that it can serve as a basis for selective pricing.*

Pricing for the Landscaping and Retail Sales Markets: These market segments generally do not represent large volumes. The customers often are do-it-yourself individuals who are not as price sensitive as customers involved in competitively bid projects.

Volume Pricing: Large and frequently placed orders often justify volume discounts because economies of scale come into play, thereby reducing total production costs. This is true, for example, in situations involving repeat or steady customers who place significant orders in terms of size and frequency. This type of customer, for example, may be a ready-mix concrete producer, a concrete block manufacturer or a prestressed concrete producer.

Pricing for a Large Project: The large project market segment is covered under bidding later in this section. Often large projects are priced at a level lower than other segments because fixed costs are spread over a large, long-term volume of aggregates.

Responsibility for Setting the Producers' Prices

The individual responsible for establishing product prices varies with the size of the firm. In smaller companies, the top management generally sets prices. In larger firms, the prices may be established through the budgeting process or are set by the marketing department with counsel from the sales and finance departments.

Price Incentives

Price incentive methods can be employed in the industry that may result in reduced prices for the customer. Incentives can be in the form of discounts for early payment or large purchases. The important factor with price incentives is that all customers competing in the same market segment must be treated equally. In other words, a producer cannot use discriminatory pricing policies.

Discounts for Early Payment: Common discounts in the aggregates industry involve a 1 to 3 percent discount if invoices are paid within 10 days of receipt. If payment is not made within this period, the producer expects the invoice to be paid in full within 30 days of receipt of the invoice.

Quantity Discounts: Quantity discount pricing is used to encourage a buyer to purchase all or a large portion of his or her requirements from one producer. For example, a producer may price a product at $4.80 per ton for a volume of less than 10,000 tons. Once the buyer has purchased more than 10,000 tons, a discount of $0.10 per ton may be given for all subsequent purchases. This can be attractive to a buyer who has an option of buying from another supplier.

Pricing Decisions that Involve Bidding[13]

Depending on market areas, competitive bidding and negotiated prices are common practice in the aggregates industry. There are three types of competitive bidding: *closed, open* and *negotiated.*

Closed Bidding: *Closed bidding* is often used by government agencies or institutions. The bids are submitted in writing and are sealed. All bids are opened at a specific time (as stated in the bid proposal) at a public meeting to which all bidders are invited. The lowest bidder, assuming that the bid meets specifications, receives the award.

Open and Negotiated Bidding: In open and negotiated bidding, the process is less formal. The buyer announces that bids will be received until a certain date. Prior to the actual bid date, the producer can discuss the merits of its products and services, and the buyer's requirements. The producer can even consider ways to reduce the cost of production or increase the value of the product or service. After the buyer and producer have an adequate understanding of the project and its requirements, the producer quotes a price. Based on the buyer's judgment of what is the best value, a decision is made to purchase from a specific supplier. In many cases, the buyer does not decide to purchase from the lowest bidder because consideration is given to the value of benefits other than a producer's price.

A significant portion of construction aggregates is used in contracts where the low bidder is selected by closed bidding. In the bidding process the aggregates producer must obtain as much information about the project as possible, such as product specifications, timing, service and the competitive environment. Once this background information has been obtained, the producer quotes prices to firms bidding on the project.

9.6 Developing a Marketing Plan

The previous sections in this chapter introduce marketing and sales that will help the aggregates producer develop strategies for the markets they serve. Organizations cannot survive by simply reacting to new developments as they occur. This type of ad hoc marketing results in inconsistent actions and expenditures and leaves the organization vulnerable to more forward-planning competitors. Each firm must take a planned approach to the marketplace. Most leaders in the aggregates industry are active and action oriented. If marketing plans are to be developed, considerable thought must be given by the leadership of the firm to introduce a planning culture into the organization.

Philip Kotler stated in *Marketing Management-Analysis, Planning and Control*[2] that "Top management needs a plan for selling its managers on the benefits of planning. The main benefits of planning are that it:

- Encourages systematic thinking ahead by management;
- Leads to a better coordination of company efforts;
- Leads to the development of performance standards for control;
- Causes the company to sharpen its guiding objectives and policies;
- Results in better preparedness for sudden developments; and
- Brings about a more vivid sense in the participating executives of their interacting responsibilities."

Kotler further discussed the evolution of business planning by giving the five stages that businesses pass through on their way to sophisticated planning. In the aggregates industry, companies can be found in each of these stages:

Unplanned Stage: When companies are first organized, their managers are so busy acquiring funds, customers, equipment and materials that little time is available to plan. Management is engrossed in the day-to-day operations required to survive.

Budgeting System Stage: The company eventually installs a budgeting system to improve its control of cash flow. Management estimates total sales for the coming year and the associated costs and cash flows. Department managers prepare budgets for their departments but do not become involved in detailed planning.

Annual Planning Stage: There are a number of approaches to the annual planning stage, but the most successful is known as *goals-down, plans-up planning*. Following this approach top management looks at the company's opportunities and requirements, and sets corporate goals for the year. The various units of the company are responsible for developing plans to help the company reach these goals. These plans, when approved by top management, become the official annual plan.

Long-Range Planning Stage: In this stage, management realizes that annual planning should be preceded by long-range planning. The annual plan should be a detailed version of the first year of a long-range plan. Normally, long-range plans are for periods of up to five years. They are reworked each year as the environment changes and the long-term planning assumptions are reviewed and updated.

Strategic Planning Stage: Finally, the company understands that most of its planning deals with its existing businesses and how to keep them going and does not look at the opportunities and threats that may exist outside its current business. It then starts to re-examine which businesses it should allow to grow, maintain the same, harvest or terminate, and which new businesses should be entered. Strategic planning deals with efforts to keep the whole corporation optimally adapted to its best opportunities in the face of a constantly changing environment.

As part of the company planning process, marketing plans are an important element of all stages of planning sophistication described above.

Marketing Plan Profile

A *marketing plan profile analysis* is performed to understand more clearly the external and internal forces that will influence the company's future. The same general approach can be used for a marketing profile analysis as employed in Section 9.2 for a market position analysis. Important considerations in developing a marketing profile are summarized in Table 9.4. The external analysis summarized in Table 9.4 identifies opportunities and threats to the company. The internal analysis identifies strengths and weaknesses of the company.

Table 9.4 Important Factors in Developing a Marketing Plan Profile

1. External Analysis:
• *Key External Forces:* Evaluate external forces over which the company has no control. Examples include trends in the economy, regulations, technology and demographics of users; • *Other Factors:* Ideally this study also includes size, growth, key success factors and an analysis of the industry structure such as consolidation, greater fragmentation, increased emphasis on service and changes in distribution channels; • *Competition:* Identify the competition, on what basis they compete and their strengths and weaknesses; and • *Customers:* Evaluate factors influencing customer purchases and how these factors change over time, unmet needs, the process customers use to decide upon a purchase and if this is changing and a way to target specific kinds of customers.
2. Internal Analysis:
• Perform analysis of profitability, growth and market share; • Review current strategy, rationale and problems; and • Review organizational structure, people, systems and culture.

Example Marketing Plan Profile

The following example of a marketing plan profile for an aggregates base producer can be used as a guide for the marketing plan for other areas or as a tool in segmenting markets or product lines.

1. Objectives:

a. Within five years, increase the crushed stone base market share from _____% to _____%.

b. Improve the profit margins for the crushed stone base from $_____ per ton in the current year to $_____ per ton in five years.

c. Increase the sales of crushed stone base from _____ tons in the current year to _____ tons in five years (annual growth rate of _____ %).

2. Strategic Recommendations:

a. Identify the high volume specifiers and high growth development areas. Bundle the total marketing program based on product performance, value and economy.

b. Target the parking areas and city streets, where the firm is a low cost producer. First, compete on delivery, product value and customer satisfaction, second on price.

c. Identify the existing supporters of crushed stone base for client maintenance.

d. Identify the product areas where value is added and reduce the costs when possible to gain market share. Focus on customer satisfaction, access to the customer service department for project quotes, delivery, material loadout and availability and material placement.

3. Marketing Program Design:

a. Target the markets and priorities:
- Architects and engineers in the private market segment of parking areas and street design;
- Large specifying firms that generally work in areas where the firm has the largest market share;
- Growth areas that have street projects — both new and reconstruction;
- Public agencies that will consider possible test sections to compare performance of crushed stone with competing products.

b. Product positioning:
- Best value in the market;
- Proven performance.

c. Pricing policy:
- Defend markets when the firm is the low cost producer;
- Compete aggressively when the firm has an opportunity to increase its market share.

d. Promotional programs:
- Have the __________ (company representative) placed on grading and on the base committee of the state department of transportation by __________ (date);
- Have the __________ (company representative) work with the Construction Specification Institute's committee on aggregates base by __________ (date);
- Develop a customer satisfaction survey by __________ (date) and inform the decision

makers about the positive response by __________ (date);
- Publish a quarterly technical newsletter by __________ (date);
- Develop a technical assistance hot line for users and specifiers by __________ (date);
- Exhibit or attend __________, __________, __________, association conventions on the following dates: __________, __________, __________.

e. Distribution of promotional materials:
- To the top 50 public and private specifiers;
- To the top 100 customers; and
- To all local specifiers of public projects--national, state, county and city.

4. Revenue Share and Profitability:

a. -__________ tons @ $______ per ton margin; Gross profit of $______.
b. -__________ tons @ $______ per ton margin; Gross profit of $______.

5. Measurement/Tracking System:

a. Develop a map that identifies public areas that specify a crushed stone base. Have the map completed by __________ (date) and update it monthly;
b. Monitor the win/loss ratio of all project bids using the crushed stone base. Have the form completed by __________ (date) and update it quarterly;
c. Chart the sales against the forecast on a monthly basis;
d. Review the results of the customer satisfaction survey by __________ (date);
e. Monitor the activity of hot line inquiries quarterly;
f. Monitor the actual tons, margins, and gross profitability against the forecast on a monthly basis as illustrated in Figure 9.2; and
g. Monitor the inventory/sales backlog regularly.

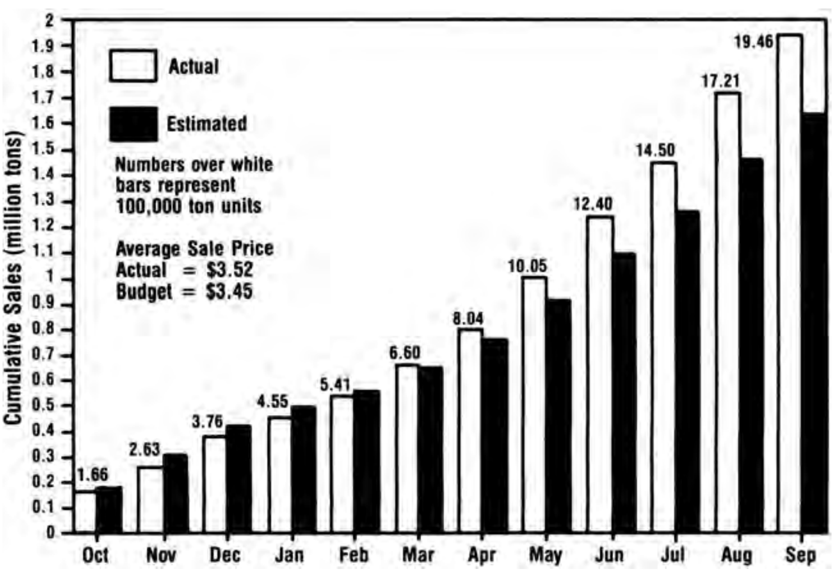

Figure 9.2 Comparison of estimated and actual sales.

An aggregates firm that uses a marketing plan format similar to the one previously described will devote much time and thought to understanding its market. As a result, the necessary tools will be developed to influence the market positively in its favor.

Not all aggregates producers use formal planning, and not all companies that use it use it well. Some of the benefits of formal planning include more systematic thinking, better coordination of company efforts, sharper objectives and improved performance measurement. As a result, all formal planning ultimately should lead to improved sales, profits and customer satisfaction. Marketing input is necessary in formulating various company plans including the corporate, financial and operational plans.

9.7 Summary

In the construction aggregates industry of the future, larger and more sophisticated equipment will produce more products at higher rates and with greater product uniformity. More restrictions will be placed on aggregates reserves by government agencies, and customers will require higher quality products greater volumes. The whole process will happen faster than the industry has ever experienced in the past. Fewer companies will compete for the market. They will be highly skilled in all phases of the aggregates industry.

Successful companies will be those that are sensitive to the marketplace and quickly respond to its ever-changing environment. Aggregates firms that continue to believe that success is based on a single orientation, such as production or finance, will not be as successful as those that consider a balanced approach where all management functions share equally in the firm's decisions.

Marketing of construction aggregates offers one of the greatest untapped opportunities in the industry. Marketing is not a black box from which magical solutions spring at the request of management. Marketing is more like a recipe entered into a cooking contest: many ingredients are properly combined and time is allowed under the proper cooking conditions before being presented to the judges for evaluation. In the case of the aggregates industry, the judges are customers, employees, corporate management, owners and communities in which the company operates.

A marketing-oriented company considers how it will position itself in the market. That is, will the company emphasize low cost, high quality, technical support, a particular market area, or will it select specialty product segments? Conscious and planned decisions are made on what position it wants the marketplace to believe it represents.

Quality always will be a significant factor in determining the success of aggregates companies. Quality does not just stand for product quality but also for a quality organization. Quality companies make quality products and they respond in a quality manner to the needs of their customers, employees and their communities.

Research and development of aggregates products and the products manufactured from aggregates require constant attention. The mineralogical composition of construction aggregates varies from deposit to deposit. Customer application of the aggregates is becoming more demanding. Only through research and development can an aggregates company know the strengths and weaknesses of its products as well as the strengths and weaknesses of its competitors' products.

The construction industry has many opportunities to decide what building materials are used. Many different products can be used and some of them are not construction aggregates. The products may be by-products from an industry that has little or no direct connection with the construction industry. Reaching the decision maker during the design stage can mean the difference between large volumes of aggregates being employed on a project or none. Through product knowledge, seminars with specifiers, trade shows and industry involvement, an aggregates company can favorably influence construction aggregates specifications.

Whenever customers ask about price, what they really are asking about is value. *Customers want to obtain a fair value for the money spent. Customers will buy the product if they are convinced they are receiving good value.* Construction aggregates tends to be in a price inelastic market. That is, little increased sales volume is created by lowering the price of a product. This differs from the consumer markets where a price reduction can significantly increase sales volume.

Product pricing may appear simple but it involves many cost centers in a company. Competitive market conditions also must be considered. In the area of pricing, antitrust laws must be clearly understood by the people establishing the price policy and selling the products. Prices have to be equal to all buyers in the same market and business, and discussions involving prices of products cannot take place with competitors.

Planning occurs in many forms. Planning can take place in day-to-day activities or it may be in the form of a five-year plan. Unless a conscious effort is made to specifically plan for expected results, the producer is unable to position itself for maximum benefit. Marketing plans are like road maps that outline the many variables a business will encounter during a particular period. A marketing plan must be a written document. The plan may not be that important, but the thought and effort that goes into developing the plan is very important. Management can gain an understanding of the internal and external strengths and weaknesses through a cooperative effort in developing a marketing plan.

The marketing concept will grow in the aggregates industry. Companies that accept marketing as an equal partner in the management team, learn the marketing principles and hire and train competent staff also will grow.

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Chapter 10
Product Transportation and Distribution Systems

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10.1 Introduction

Truck, rail and water are the three basic transportation modes used to distribute aggregates to consumers. Generally speaking, aggregates are used in manufacturing plants (portland cement, ready-mix concrete, hot mix asphalt, block, etc.) or at construction sites. In both cases, aggregates must be shipped from the point of production to the point of use.

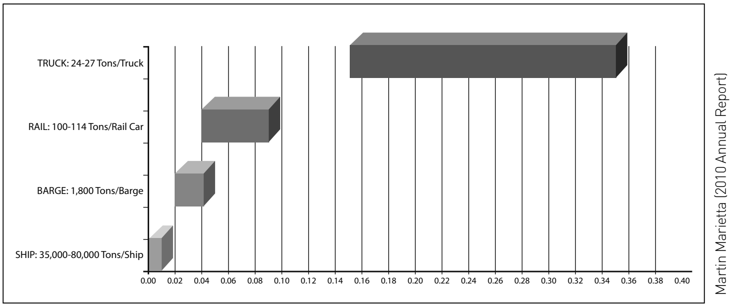


Figure 10.1 Transportation Cost per Ton per Mile

Transportation costs are an important factor in aggregates sourcing decisions due to the high unit weight of the product and the large number of sources. Truck delivery requires the lowest capital investment. Rail and water modes involve significant infrastructure investments at the plant and at the destination (Figure 10.1).

When shipping distances are less than 100 miles, trucking is generally the most economical distribution method. Given typical industry shipping distances, trucking is the principle form of aggregates transportation in most areas of the United States and is generally provided by third parties or by the customer. A typical truckload of aggregates is between 24 to 27 tons or less. Truck payloads vary by the number of axles and by state. For example, the state of Michigan allows double-axle trailers up to 46 tons.

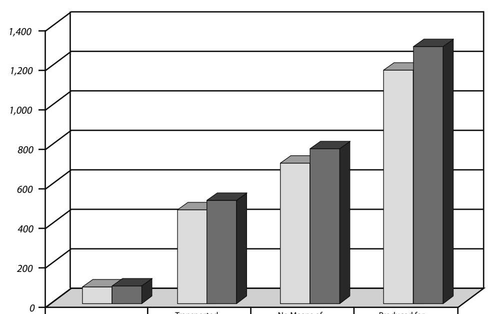
The uneven geologic distribution of quality aggregates, coupled with depleting local reserves and increasing permitting difficulties, creates the need for cost effective long-haul transportation methods. When shipping distances exceed 100 miles, rail or water transportation methods often produce economies of scale and the lowest cost option.

Rail transportation is provided by a collection of Class 1 and Short Line railroads; shipments tend to be focused in areas where the origin and destination are on the same rail line or Class 1 plus connecting short line combination. Rail cars can hold approximately 100-114 tons of aggregates; a typical train size is 50 to 100 cars. Rail can be cost effective at various distances, ranging from 25-mile shuttle moves on short lines to 250 miles for longer haul unit trains on Class 1 carriers, up to even longer distances for specialty aggregates moving in carload service. The use of distributed power (referring to the placement of locomotives throughout the train as opposed to in the front and rear only) increases the potential train size to more than 120 cars but requires additional infrastructure investment.

Water transportation involves the use of barges or ships. Barges require towboats whereas ships have their own internal source of power. Individual barge capacity can be as small as 500 tons while ocean-going ship cargos can exceed 50,000 tons. Barges frequently are grouped together for shipment to a single destination.

It is common for long haul destinations to serve also as "distribution yards." Often, distribution yards will contain a large manufacturing plant to minimize additional transportation costs. Yards will frequently use truck transportation for final delivery to end-users located in the immediate geographic area.

For the 702 million metric tons of the 1.17 billion metric tons of crushed stone produced for consumption in 2009, no means of transportation was reported by the producers. Of the remaining 464 million metric tons of crushed stone, 75 percent was reported as being transported by truck from the quarry or the processing plant to the first point of sale or use, 7 percent by rail and 7 percent by waterway. About 41.6 million metric tons of the specified production was reported as not having been transported and therefore is assumed to have been used onsite (typically in hot mix asphalt or ready mix concrete plants). Shipment by truck remains the most widely used method of transportation for crushed stone. The significant increase in the number of sales and distribution yards in the past few years and the increase in volume of crushed stone going through these sites have had a positive impact on the industry and the communities they serve. Distribution sites, supplied by rail or waterway, are located near metropolitan areas and significantly reduce the distance most trucks must travel to pick up and deliver crushed stone. Therefore, the transportation costs are reduced as is the impact of heavy traffic on the infrastructure and environment. (Figure 10.2) This is a significant factor in the industry's ongoing relationship with government agencies.



	Onsite	Transported by Truck	No Means of Transport Reported	Produced for Consumption
Metric Tons (Millions)	41.60	464.00	702.00	1,170.00
U.S. Short Tons (Millions)	45.86	511.70	773.82	1,289.70

1 U.S. Short Ton = 2,000 Lbs.
U.S. Ton is also known as a Short Ton
Rail and truck shipping is measured in U.S. Tons or U.S. Short Tons.
Water shipping is measured in metric tons.

Figure 10.2 2009 Nationwide Production and Distribution Conversion Table

The balance of this chapter will explore the factors and considerations necessary for creation and operation of an effective aggregates distribution system.

10.2 Truck Transportation — The Common Denominator

Trucking is still the predominant mode of aggregates transportation. While trucks are the least costly to operate on an hourly basis, they transport 24 to 27 tons with a single trailer over federal highways. The sole governing limit for the interstate system is 80,000 pounds gross vehicle weight. Typically, state limits for secondary highways are 85,000 pounds. A typical load is made up as follows:

	Aluminum Body	**Steel Body**
Truck (Tractor)	17,000 lbs. (8.5 tons)	17,000 lbs. (8.5 tons)
Truck (Trailer)	15,000 lbs. (7.5 tons)	18,500 lbs. (9.25 tons)
Payload (Material)	48,000 lbs. (24.0 tons)	44,500 lbs. (22.25 tons)

Depending on its number of wheels, number of axles and length, one truck can carry up to 27 tons per load on normal streets, highways and bridges.

Truck Types

A wide variety of trucks is used to provide aggregates transportation. The diversity comes from a wide variation in local and/or statewide regulations across the country, as well as the diversity in the road network itself. The size and type of project underway also has a great bearing on the trucking used.

Broadly speaking, the types of trucks used for aggregates transportation can be divided into a few general configurations as follows. There are many variations or derivations of each within local markets.

1. Straight Frame Tandem Axle Dump Truck

Typically, this type of truck is some variation on the "tri-axle" layout with two (or more) drive axles. Additional "lift axles" may be used to distribute weight over more wheels when the truck is loaded. When unloaded, these axles are lifted from the road to reduce wear (Figure 10.3, see color section).

Tri-axles provide effective haulage on shorter routes, typically up to 25 miles and can be convenient for smaller contracts or projects. The shorter wheelbase allows better maneuverability than that of longer trailer alternatives. This can be an important consideration where space is limited or where the road network is restrictive. They are very popular in the Northeast, Mid-Atlantic and South regions. Following are a few noteworthy variations:

A. Super Dump Truck

This employs a liftable, trailing axle to increase the allowable gross vehicle weight. When the trailing axle is engaged, it typically rides 11 to 13 feet behind the truck itself. This spreads the load over a wider footprint allowing for more payload based on federal bridge laws. When the truck is empty, the trailing axle can be lifted from the road (Figure 10.4, see color section).

B. Tandem Truck

This is a straight dump truck that pulls a trailer, often using seven or eight axles overall to carry a gross vehicle weight up to 105,500 pounds (special permits may apply). A tandem may require more space or open road to maneuver but can be very effective haulage for longer routes, typically 100 to 200 miles. In some areas, additional trailers may be connected to form "trains" allowing one operator to deliver more material to a site. Two major types of tandems are defined:

- *Transfer Truck*
  A transfer trailer does not have its own dump function. Rather, the trailer body must be shifted into the dump truck to be dumped. To offload, a transfer operator first disconnects the trailer to dump the truckload. Then the trailer body is shifted into the truck body, secured and dumped. The empty trailer body is then transferred back to the trailer, which can be reconnected to the truck (Figure 10.5, see color section)

- *Truck and Pup*
  This type of tandem truck has a trailer with a self-contained hoist system. This simplifies the offloading process by eliminating the transfer step above. Therefore, to offload, the operator first dumps the trailer load then disconnects the trailer. After dumping the truckload, the trailer can be reconnected (Figure 10.6, see color section).

2. Tractor and Semi-Trailer

A tractor-trailer configuration can be more suitable to longer haul routes or larger projects. It also offers a wider variety of dump configurations suitable for special jobs. Typically, a semi employs a three-axle tractor that pulls a trailer with two or more axles. Additional trailers may be attached to form "trains," allowing one operator to deliver more material to a site (Figure 10.7, see color section). Following are a few noteworthy variations:

A. End Dump Semi-Truck

This configuration has a hoist system in the trailer that dumps the load over the rear end (Figure 10.8, see color section). Advantages of this configuration can be very quick unloading and possibly lower load height as compared to some tri-axle trucks. However, dump height can be very high when offloading which may result in an increased risk of instability.

B. Bottom Dump Semi-Truck

A bottom or "belly" dump truck discharges its load from the floor of the trailer (Figure 10.9, see color section). The key benefit of this is that it allows more discharge that is consistent across an area or window. Material also can be discharged without reversing the truck, unlike a rear dump, which usually reverses to a dump point. Eliminating reverse travel may be quicker and safer on some sites. Lastly, the height of the truck does not increase when discharging and stability can be maintained.

C. Side Dump Semi-Truck

A side dump truck can be very effective in certain applications, dumping into a specific load point or in confined spaces. Hydraulic cylinders on the trailer(s) discharge the load either to the left or right side of the truck. Dumping can be very quick and stability is maintained as long as the discharge is not interrupted. Additional trailers can be added depending on state regulations and how far into adjoining states the load is delivered (Figure 10.10, see color section).

Horsepower

Typically, trucks need just enough horsepower to move down the road at legal speeds, but not so much that the extra weight of a bigger engine sacrifices payload. A good average for normal duty is 450 horsepower. Therefore, a good rule of thumb is a power-to-payload ratio in the range of 18-to-20-horsepower-per-ton of payload. However, this optimal ratio may decrease as fuel efficiency becomes more important than performance. Increasing diesel prices plus the weight penalty of large bore engines (greater than 13 liters displacement) increases the economic pressure on haulage. Therefore, more fuel efficient, smaller bore engines (less than 13-liter displacement) may become more popular at lower horsepower ranges. A 400 horsepower engine, for instance, will yield a power-to-payload ratio below 18.

Hourly Costs

To generate a good estimate for hourly costs, consider the following example:

	Hourly Cost
Driver Wages and Benefits:	$25.00
Liability Insurance:	$1.00
Overhead and Dispatch:	$2.00
Supply and Repair:	$5.50
Fuel, Oil and Grease:	$50.00
	$83.50

Assuming a 24-ton load of aggregates and a 20-mile-per-hour average speed, the ton per mile cost of haulage is $0.174. Bear in mind that a typical truckload cycle includes exchange time for loading and unloading, stoplights, highway ramps and traffic congestion.

Regulations

In 1975, Congress enacted the Bridge Formula to limit the weight-to-length ratio of a vehicle crossing a bridge. This is accomplished either by spreading the weight over additional axles or by increasing the distance between axles. In addition to bridge formula weight limits, federal law states that single axles are limited to 20,000 pounds and axles closer than 96 inches apart (tandem axles) are limited to 34,000 pounds. Gross vehicle weight is limited to 80,000 pounds. The bridge weight formula and additional information can be found at www.ops.fhwa.dot.gov/freight/.

For information on state and local trucking regulations, contact one of the 52 divisions of the Federal Highways Administration to obtain details. A listing of contacts can be found at www.ops.fhwa.dot.gov/freight/sw/contact/index.htm.

10.3 Rail Transportation: How it Works

America's freight railroads are independently owned and maintained. Freight railroads in the United States fall into one of three categories:

- **Class I:** These railroads have annual operating revenue of more than $250 million, and are the "heavy" railroads that run multiple train-sets over single, double or quadruple tracks every day. Union Pacific, BNSF Railway, Canadian Pacific, Canadian National, CSX, Kansas City Southern and Norfolk Southern are the only Class I railroads.

- **Class II:** These railroads are typically regional carriers with at least 350 miles of track and at least $40 million of annual operating revenue. Montana Rail Link, Florida East Coast, Wheeling and Lake Erie, Wisconsin Southern, Kyle Railroad, Iowa Interstate and Alaska Railroad are examples of Class II railroads.

- **Class III:** These railroads are small to mid-sized lines that operate over relatively short distances and normally connect to larger, national rail networks. Most short lines were spawned by the larger railroads when they leased or sold-off low density or margin sections of track. These lines typically exist solely to haul product for a handful of customers and generally have plenty of capacity to sell. In many cases, short lines belong to a "family" such as RailAmerica or Omnitrax. This arrangement allows for daily management by local operational staff and crews with centralization of many support and administrative functions.

Considering that it takes just 1.0 horsepower on average to move a ton of material across the rails, it is obvious that low-value bulk products like rock and sand can be moved efficiently via the rail network, along with high volume commodities such as coal and grain. Railroads typically favor movements of long strings of identical carloads (typically 80 to 120 cars) known as "unit trains." These trains cycle from origin to destination on a regular basis, so the cycle time, crew requirements, power (locomotive) needs and siding lengths are nearly the same for every move. Contrast these shipments with single carload and 20 or 30 car movements that are called "manifest traffic." This type of move requires more handling by the railroad and therefore usually a higher freight rate. This is due to the cost of assembling a 120-car train made up of 20 or 30 customers' shipments moved in "cuts" of a single car or more. On any given day, you can see trains of boxcars, tank cars, automotive racks and flatcars full of every type of product. Each cut had to be stopped in intermediate yards and switched out to the final destination. The number of stops and starts and a crewmember on the ground pulling coupler handles multiplies the time as well as the cost. Depending on the railroad and operating territory, shipments of less than 60 to 80 cars may be less than ideal and may not merit unit train pricing.

Railroads are always interested in new business. Careful planning and the exchange of information are critical to a successful rail move. This will help railroad management to understand customer needs and work for its customers to develop the optimal combination of service, equipment supply, rates and facility design. The sales and marketing departments will provide rates so the customer can evaluate the potential for rail shipment. Most carriers have industrial development specialists to assist potential customers in locating a suitable site on their line or to develop a conceptual track plan.

In order to judge the merits of a potential rail move, another critical factor is the "controlling grade." All railroads have some degree of slope to overcome, and the maximum slope between the origin and destination will dictate how much horsepower to assign to the "engine consist." On a 200-mile run, it is conceivable that just three engines could handle a trailing load of 12,000 tons of cars and material, but as little as a 0.4 percent change of grade can require a fourth power unit for just a few miles. Imagine the risk to the railroad if a train stalled on a hill for lack of speed and traction! Therefore, the pulling power must always be more than enough to overcome the worst grade. Typically railroads will use a 1:1 ratio (tons per horsepower) to account for grade variations.

A critical study of the U.S. rail map yields the fact that rails tend to be adjacent to rivers and streams. Following the relatively flat profile of the Platte, Missouri or Arkansas rivers made sense when the rails were first laid out and still does today. Fortunately, most sand and gravel deposits lie in the floodplain of these waterways (Figure 10.11, see color section).

Rate Construction

Rates depend on a number of factors. Rates on most Class I railroads may range from $0.035 to $0.135 per ton per mile, with an estimated average near $0.055 per ton per mile. In addition to the unit train length and frequency of cycles, the freight rate will be influenced by length of haul, car type, car ownership, annual volume, shipment seasonality and number of rail carriers. Also important are the dynamics of transportation market supply and demand. Rail rates may be standard or public tariff rates; a rail carrier also may negotiate lower rates if market conditions or volumes warrant.

Rail rates are usually quoted on a "per car" basis, so the tonnage in each car will be important to maximize. Rates may also be quoted on a "per ton" basis, especially when the shipper provides certified origin scale weights. Lighter unit weight materials might fill the entire volume of the car before the tonnage reaches the gross limit.

1. Loading and Unloading Cycle Times

Generally, a string of cars needs to be "indexed" past a stockpile or load-out bin in order to fill them. The same is true for the unload cycle. Figure 10.12 (see color section) depicts a typical rail terminal layout. Whatever method is used to move material into the car, (front-end loader, overhead hopper or conveyor) the actual time consumed per car is governed by the indexing speed, how fast a particular aggregates flows from the car, and the take-away rate of the conveyors.

2. Switching Requirements

An 80-car train is longer than 4,000 feet, so a normal event is to break the string in segments that fit the available track length and hook-back into a long string when full or empty.

3. Interchange

If more than one railroad pulls the train or carload shipment from origin to destination, there will be a fee charged by the receiving railroad to interchange from one system to another. This can vary greatly with the physical layout of the tracks and business volume considerations. Rates may be through rates (inclusive of all carriers' line haul charges), or may be from origin to the junction point with a connecting line, in which case the carriers will bill their line haul charges separately.

4. Yard Limits

If the origin or destination lies within the yard limits (or sometimes known as the "switching limits") of a subdivision of the railroad, a new crew may have to be dispatched to place the car at the industry for unloading. The entire shift cost of that crew must be applied to the rate. For example, if the receiving yard is outside of the yard limit of Chicago, then the road crew can spot the car(s) in the industry track as they travel en route to their final destination.

5. Hours of Service

The Federal Hours of Service Laws governs the length of time train service employees can work in a single shift (12 hours) and the amount of time off between shifts (10 hours). Freight rates also will consider how many "crew starts" will occur between each origin and destination.

6. Car Ownership

Cars may be supplied by the railroad, customer or both. Normally, railroads will provide a discount for shipper-supplied equipment. Private cars must be approved by the railroads over which the cars will travel. Rates in privately owned or leased cars normally include free movement from the unloading point back to origin for their next load. Customers may purchase new or used cars, or may lease them from leasing companies. Cars may be leased on a full service basis (lessor absorbs running repair costs) or on a net lease basis (lessee absorbs running repair costs).

Car Types

Most railcars, including open-top bottom-dump hopper cars that were built after 1986, are rated for 286,000 pounds gross weight, the new standard in the industry. Most cars tare-out at about 55,000 pounds, leaving 231,000 pounds or 115 tons of capacity available for rock or sand. Rail rates are quoted on a "per car" basis, so the tonnage in each will be very important to maximize.

1. Hopper Car

A typical hopper car has two to four outlet doors and averages 44 to 53 feet from coupler face to coupler face (Figure 10.13, see color section)

2. Gondola Car

A gondola car (Figure 10.14, see color section) is normally used for materials such as erosion stone or riprap. They are rarely "purpose-built" cars; they usually are converted from scrap steel or ore mining service. Loading is easier due to the low sides and flat bottom; however, unloading requires a backhoe or a crane.

3.Ballast or Control-flow Car

A ballast or control-flow car (Figure 10.15, see color section) has special doors that allow ballast rock to be spread either outside or inside the rails while the car is moving. Most railroads do not supply specialized ballast cars for revenue shipments of track ballast, but instead may supply a standard bottom drop hopper.

4. Rapid-discharge Car

A rapid-discharge car (Figure 10.16) has very steep end slopes and has "double doors" on the bottom discharge pockets. Viewed from above, this type of car has virtually no bottom. Doors may be equipped for pneumatic operation.

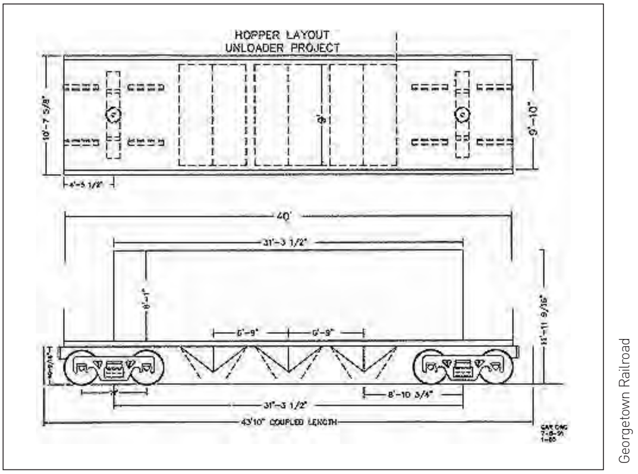


Figure 10.16 Ortner Rapid Discharge Car

Unloading Systems

Like any other part of rock and sand production, unloading railcars is all about maximizing flow rates and minimizing exchange time. Indexing a string of cars past a central unload point (the car doors open, the material is dumped into an under-track pit, the doors close again) is normally a six to eight minute process (Figure 10.17, see color section).

Bigger load-out conveyor belts and deeper under-track hoppers can improve the per-car timeframe. However, moving the cars into position takes an inflexible amount of time. This time is extended when an 8,000-ton train is broken down to several cuts of cars, causing "no flow" conditions for 10- to 20-minutes-per-hour while a new cut of cars are switched into position. Therefore, the optimum length of track for unloading is twice the length of the expected train with an under-track pit in the middle.

Conversely, if one or more backhoes can be placed on top of a car, the train can be left stationary and the backhoes can load trucks that shuttle the material from trackside to stockpile. This can be a very cost-efficient method to employ if the unload track length is limited. In addition, several manufacturers market self-propelled belt unloaders that extend under individual car doors and rapidly convey product to waiting trucks (Figure 10.18, see color section).

Loading Systems

Putting rock and sand into a railcar is much easier than getting it out. The simplest and most continuously used method is one or more front-end loaders feeding eight to 12 buckets of material from a centrally located stockpile. Most 7-cubic-yard loaders are capable of loading 700 to 900 tons per hour and can be used best by building stockpiles in the right quantity and location (Figure 10.19, see color section).

Other common loading systems involve some sort of overhead bin whereby gravity discharges material into a moving rail car below the outlet gates (Figure 10.20, see color section).

The cost of 150 to 300 ton overhead bins elevated over a track, while considerable, is a fraction of the infrastructure needed to keep the bins full while loading a moving unit train at over 2,000 tons per hour. This system requires high volume conveyors as well as a "live" product stockpile with multiple drawdown points to feed to the conveyor (Figure 10.21, see color section).

The system depicted on Figure 10.22 (see color section) loads out ten (10) cars per hour of various sized materials direct from production to rail bins.

In addition to the shortest possible timeframe, other variables are unique to railcars, payload accuracy and load distribution. Railroads generally will quote per carload rates, so it is up to the shipper to load the car to the maximum payload allowed.

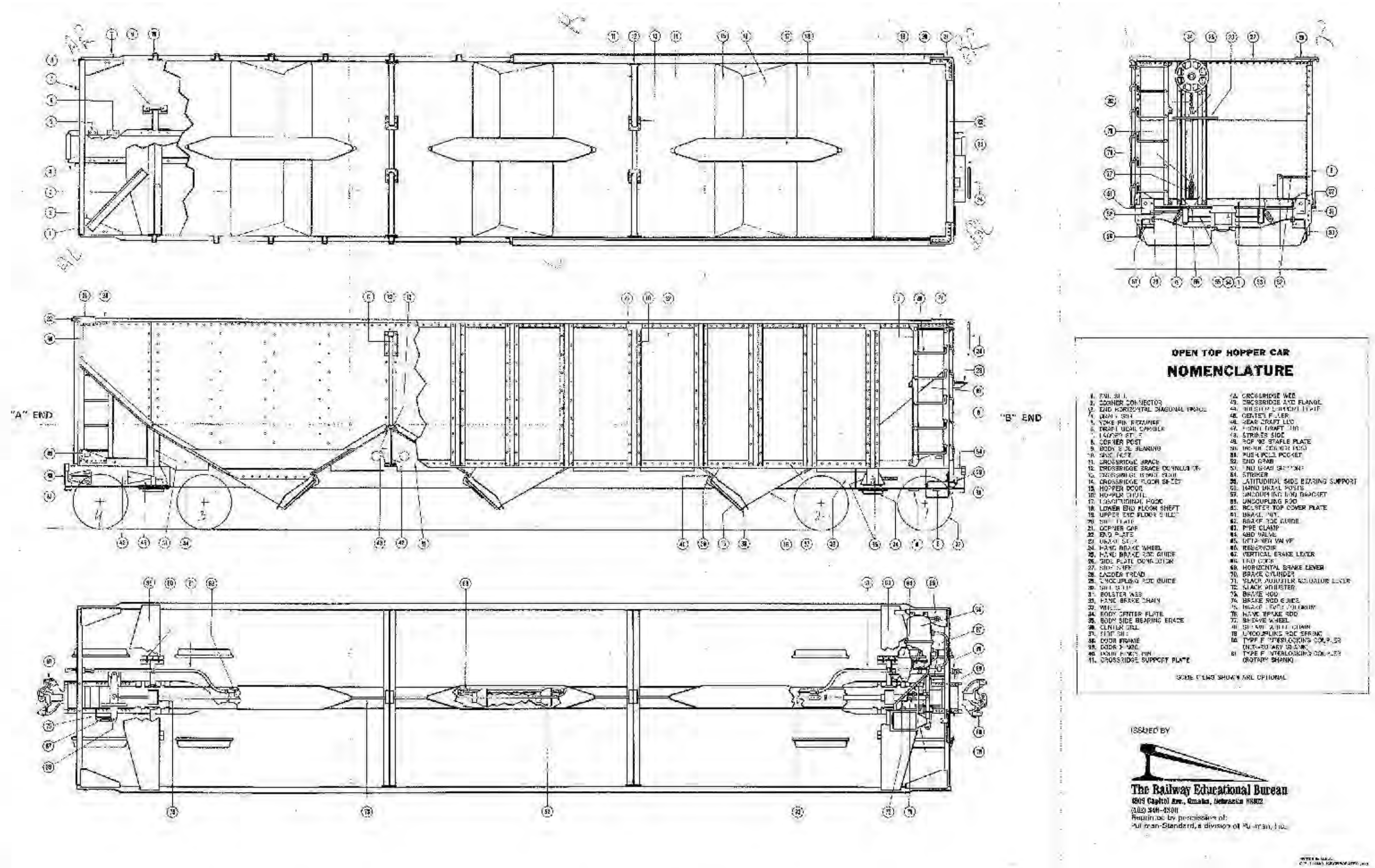


Figure 10.23 Open Top Hopper Car Nomenclature

Pullman, Inc.

Figure 10.23 shows typical railcar identification and specification markings for an open top hopper car.

One or two tons "short" and the cost of the freight for the actual tons hauled goes up. On the other hand, overloading a railcar or unevenly distributing the weight can cause a car to derail, so naturally the railroads are quite specific on how the cars are filled.

1. Truck Load-out

The same considerations apply for truck load-out, but the size and complexity multiply as the number of products increase. For example, a typical quarry produces at least four sizes of stone: #57 rock, #8 rock, chips and #4 fines. While these bins are much smaller than those used in rail loading (typically 50 to 150 tons), the sheer number and filling via conveyors makes for a different equation (Figure 10.24, see color section).

2. Ship and Barge Load-Out

Ship and barge load-out present a vastly different set of considerations. When loading a 40,000 to 80,000 ton ship, the lay-time daily costs are the same as the actual days at sea. Therefore, loading rates of 4,000 to 6,000 tons per hour are justified in order to drive the shipping cycles per month higher. Stockpiles for this type of loading are about twice the per-shipload tonnage. The difference in conveying 1,000 tons per hour vs. 6,000 tons per hour is approximately three times cost due to higher capital and operating costs.

Operations. Safety, Rules and Regulations

1. Day-to-day Operations

Railroads have added a large number of electronic/web-based tools to facilitate daily operations. Car ordering, bills-of-lading, car releases, location tracking and payment of freight bills all can be done online with many railroads. Telephonic contacts also are available for problem resolution. The railroad's sales and customer service departments will assist with getting your shipments started as smoothly as possible.

2. Safety

Safety is paramount in any operation involving rail. Railcars roll easily and quietly, and employees must be alert at all times and use proper safety equipment. Personnel should be fully trained on working around tracks and railcars, operating car moving equipment, using switches and derails, setting hand brakes or using air brakes, opening and closing doors, and checking cars that are safe for movement. In addition, procedures need to ensure loads are balanced properly in the car and cars are not overloaded. Railroads utilize en route detectors to ensure cars are properly loaded and may assess large charges for overloaded cars. Communication procedures with the railroad are important so that customer personnel and railroad crews safely coordinate their respective operations when cars are being delivered or pulled. Customers also are responsible to maintain their track for safe operation. Caution must be exercised during unloading to ensure material is flowing freely from all open outlets, otherwise a car may become imbalanced during unloading and tip onto its side. Some materials are difficult to unload and require a car shaker. Ground or side-mounted car shakers are preferable to overhead car shakers; they are quieter and more efficient since they place the shaking force on the bottom chord instead of the top chord of the car structure.

3. Rules and Regulations

Each individual railroad's rules and tariffs provide for additional charges to be assessed where applicable. This includes charges for demurrage (cars not loaded/unloaded promptly), overloaded cars, weighing cars or diverting cars en route, and in some situations, for moving empty private cars. Tariffs usually are posted on the carrier's website.

For information on railway rules and regulations, please visit www.fra.dot.gov/rcc/pages/fp_49.shtml.

10.4 Receiving and Distribution Yards

The ideal layout for an unloading and reloading site is an area long enough to hold the entire string of cars and wide enough to accommodate stockpiles that equate to two trainloads. Placing three or four 20,000 ton stockpiles in such a way to allow for truck and loader access at all times is a fundamental challenge. High volume yards generally move the material by flat conveyor as far from the unload point as possible and then transfer to stacking conveyors that will build 50-foot high piles. Additional piles of other products can be readily placed by adding portable "run-out" conveyors so that a broad arc around the primary flat conveyor head pulley can be formed. Truck and loader traffic is then routed to the outside perimeter of the various piles (Figure 10.25 and Figure 10.26, see color section).

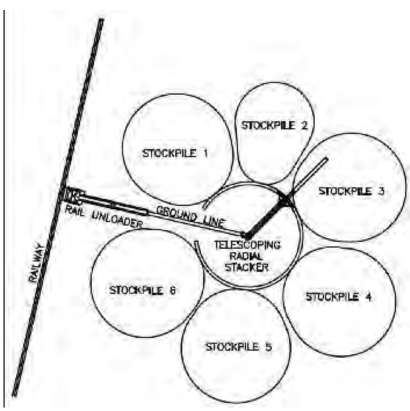


Figure 10.25 Ideal Layout for an Unload/Re-load Site

An additional consideration of "inventory turnover" bears some attention. Generally speaking, a stockpile of ¾-inch concrete rock occupies about two acres. This "footprint," once established, has a base of material that is pounded into the soil from loader and truck traffic as well as the weight of the material itself. After 10 or 15 cycles of full-to-empty stockpiles, this base reflects the shrinkage or "stockpile loss" of perhaps 8,000 tons of product. Once established, this base is a platform that prevents contamination of smaller or larger rock fractions. It is therefore good practice to stack the same product repeatedly only on its designated footprint. Predicting the turnover rate in turn becomes the main consideration when scheduling trains. For example, if the pile is depleted in two weeks, then a train has to be anticipated for that occurrence. Put another way, if the train or ship shows up too early, then there is not enough room to hold the new product. Conversely, if the train or ship shows up late, then a mad rush of customers shows up demanding to have their orders filled. Multiply this scenario by four or five products and the issue of footprint size and transportation cycles gains some clarity in the planner's mind.

Many unloading yards have a ready-mix concrete plant and/or an asphalt plant to eliminate a part of the supply chain, minimize off-site handling and reduce local truck traffic. The material stockpiles for these operations require thoughtful planning as well. Good practice demands a front-end loader "tramming" distance between the pile and feed point of less than 250 feet. A longer tram equals fewer tons per hour or a bigger (more expensive) loader. The ideal solution is to dedicate stockpiles solely for an internal plant's use and restrict outside customers to other piles. This scenario usually requires building piles during off-production hours to allow conveyors to block normally open lanes for trucks and loaders. Another "ideal" solution is to the fill feed bins that are large enough to store a normal day's production during off-peak hours.

The majority of the above discussion requires a time-consuming amount of conveyor moves. Delaying the unload cycle to do this is not usually feasible, as a unit train or ship, because of very high daily costs, has to keep moving. The only solution is to limit trainloads of material to a single product or as few products as possible based on origin production constraints.

Without question, the size and shape of an aggregates rail yard will dictate the available pile footprints and the train or ship cycles. Rigorous planning, demands for other types of rock or sand as well as big demand fluctuations will inevitably occur. It is always prudent to have extra space available for the surge when it inevitably occurs.

10.5 Barge Transportation

The heartland of America has a large number of navigable rivers. Since the early settling of the United States, these waterways have been expanded and improved to facilitate the movement of freight by water. In addition to this river system, the Gulf Intracoastal Waterway stretches from Brownsville, Texas, along the Gulf Coast to Apalachicola, Fla. Navigation also is conducted in a more limited scale along both the East and West coasts of the United States. All navigable waterways are maintained by the U.S. Army Corps of Engineers with the Coast Guard being responsible for establishing and enforcing safety regulations.

Aggregates are moved on water by hopper (Figure 10.27, see color section) or flat deck barge (Figure 10.28, see color section). While flat deck barges come in a variety of sizes, hopper barges generally are 35 feet wide and 195 feet long. A barge this size carries about 1,800 tons of aggregates when loaded. The individual barges are attached together to form tows for movement by towboats. The size of each tow depends on the river to be traveled and the size of the boat. On the Ohio River, 15 barge tows are the standard. On the lower Mississippi River, where there are no locks (an enclosure used in raising or lowering boats and barges from level to level), tows containing 30 to 40 barges are not uncommon. The size of boats used and their horsepower is decided by each owner. The most powerful towboats are used on the lower Mississippi – some have engines with up to 10,500 horsepower.

Advantages of Barges

Barges have several characteristics that are ideal for moving bulk materials. First, barges are designed to carry large quantities of materials. A normal hopper barge on an inland waterway system is capable of carrying 1,800 tons while deck barges generally carry 1,000 to 1,400 tons depending on their size and the height of walls on the barge. Secondly, barge transportation is inexpensive when compared with other forms of transportation. Less energy, labor, and overhead are required to push a load on water than to pull the same tonnage over land. The inland waterway industry transports about 12 percent of the nation's freight for about 2 percent of the nation's total freight bill.

Barge Line Rate Regulation

Since movement of bulk commodities by water is not subject to economic government regulation, most barge movements are covered by an agreement between the shipper or receiver and the barge line. This agreement covers, among other things, the responsibilities of each party during the loading and unloading operations and the rates for haulage and demurrage. These conditions, including the rates, are negotiated by the respective parties and are not public knowledge. The amount of competition for the transportation business influences the rate paid. Changes in the rate are specified in the agreement and usually are based on the actual cost or some agreed-to index. The normal items covered are labor, fuel and supplies.

For barges, the average cost per ton-mile is $0.20 to $0.25.

For information on inland waterway rules and regulations, please visit www.navcen.uscg.gov/?pageName=regContent.

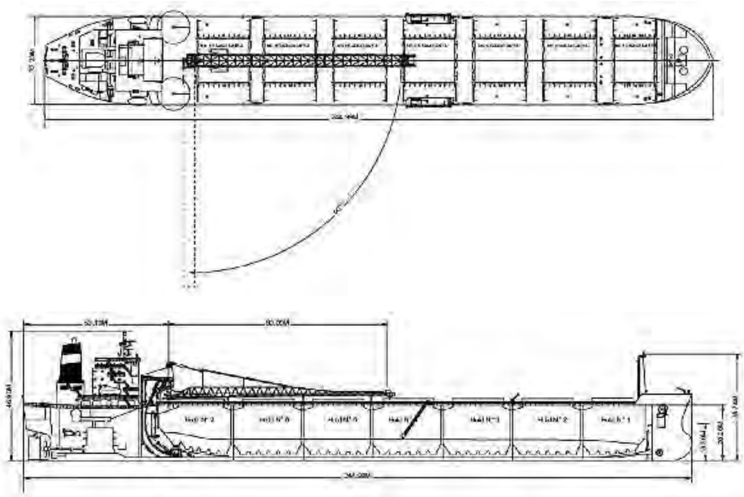
10.6 Ship Transportation

Large self-unloading ocean-going ships (Figure 10.29, see color section) carrying large quantities of aggregates have gained a significant portion of the transportation of aggregates into the United States in recent years. Historically, the thought was that the low unit price of aggregates and abundant supply would prevent foreign sources from exporting to United States markets. However, access to local sources of material has been hampered by increased regulations, environmental concerns and NIMBY ("Not In My Back Yard") mentality. The use of large bulk ships has offered alternative relatively low-cost sources to markets located on or near deep-water ports. Aggregates are being imported into various ports along the East, West and Gulf coasts from Mexico, Nova Scotia, British Columbia and Scotland.

The ability to import low-cost products, such as construction aggregates, is a textbook case study of how economics work. Large areas along the South Atlantic and Gulf coasts do not have local supplies of good quality aggregates. The California markets are suffering from large regulatory barriers to developing sources near developed markets. The aggregates required in these areas is transported by truck, railroad or barge depending on the distance and facilities at the destination. Aggressive marketers have compared the delivered cost from inland sources with the cost of importing. By moving large volumes and using the principle of back-haul pricing (wherein another commodity moves one way but pays most of the cost associated with a round trip), aggregates imported by ship can be the low-cost alternative. For ocean-going ships, the average cost per ton per mile is $0.01 to $0.015.

The large ships used to transport aggregates are designed to handle dry bulk commodities. They have open hatches or covers through which the commodity is loaded into holds or bins in the interior of the ship below deck. Loading is carried out using a conveyor belt system or with clamshell buckets. Depending on the size of the vessel, up to 80,000 tons of aggregates can be moved in one voyage. Because each hold compartment is separate, several different sizes of material can be carried on one voyage.

Ships are either self-unloading (Figure 10.29, see color section) or depend on shore-based facilities to unload (Figure 10.30, see color section). Self-unloaders offer more flexibility in the destinations that can be served. To accomplish the self-unloading, the ship is equipped with on-board cranes that lift the material out of the hold using clamshell buckets, or with a conveyor system that moves the material out of each hold (Figure 10.31). Both systems discharge the material into receiving bins or directly into stockpiles.



CSL International

Figure 10.31 Top and Side View of CSL Acadian

As with any piece of transportation equipment, a ship must be kept in service to make a profit. Special care must be used to keep a ship's time in port to a minimum. Cargoes need to be ready on arrival and loaded as quickly as possible. The same care should be repeated at the destination. Special rights that ensure a ship priority at a berth can be negotiated to make sure a ship is immediately loaded or unloaded upon arrival. The rate per ton for ship transportation is generally negotiated through a broker. Since no economic regulation of bulk ships exists, the cost of ocean shipping is based on per ton of material moved or as a charter for the entire vessel. The contract can cover one voyage or be for a long period. Since ocean shipping includes so many functions, the industry employs a large number of personnel to keep it working. Each person is specialized in a particular area and contributes to a successful voyage.

As you can see, telescopic conveyors have become an integral part of high-volume ship unloading. All wharf space in ports throughout the world comes at a high lease premium. Therefore, building large stockpiles within a limited footprint demands a conveyor that will place material without segregating the larger size fractions (Figure 10.32, see color section, and Figure 10.33).

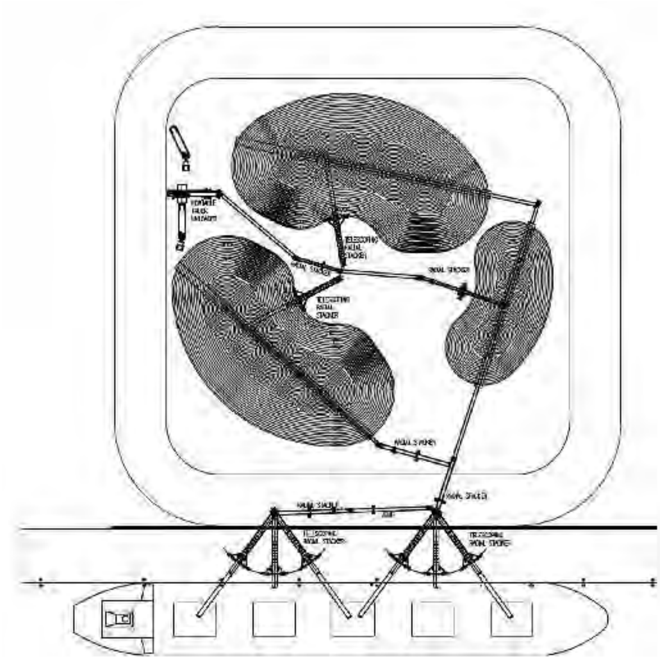


Figure 10.33 Ideal Layout

Barge/Ship Lightering

Barge lightering (or transloading) of aggregates from ship to barge, is not a new concept to the shipping industry, but is relatively new to aggregates distribution (Figure 10.34, see color section and Figure 10.35, see color section). This process allows large quantities of material to be shipped and distributed to multiple distribution depots from a single vessel. Barges can carry from 1,500 to 10,000 tons in a lightering operation.

10.7 Re-Stockpiling and Quality Control

Once a product is off-loaded and stockpiled, it normally will stay in place until loaded into a customer truck or batch plant bin. Occasionally, the pile needs to be moved to make room for other materials or it contains some deleterious size or contaminant that must be removed. Re-stockpiling and/or re-screening can be far costlier than just the hourly cost of a front-end loader. Any rock material will break down as it is handled by mechanical means. As a general rule, crushed gravel or stone will gain at least 1 percent in fines (minus #4) fraction for every time a loader bucket hits it. It is not unusual to experience 3 percent "fines gain" between origin plant stockpile tests and the receiving yard stockpiles. This is because the sliding friction that occurs during unloading and the loading process itself creates impact and wear.

Additionally, all stockpiling creates some level of shrinkage. Loader operators are carefully taught to "stay a little high" off the stockpile floor so as not to dig into dirt, base-course or old material, thereby contaminating the pile. While this is good practice, it also guarantees another 2 percent loss of product. Re-stockpiling has even more effect on this as there is inevitably minor spilling on every bucket load that is lost to the yard "floor." After repeated cycles on the same footprint, a material stockpile base will gain elevation. The cost of re-leveling this area is yet another cost to include in the planning process.

Other quality issues can occur due to contamination from previous hauls. Dirty trucks, rail cars or even ship holds can create a huge problem when they contain a larger size stone than the product being shipped. Even a quantity as low as a few wheelbarrows of "oversize" spread-out over 10 or 20 trucks or rail cars can contaminate an entire 10,000-ton stockpile. Because of this, great care must be taken to inspect and clean the vessels used to transport stone and sand.

Customers of the crushed stone, sand and gravel industry always will have careful planning expectations of quality and error-free delivery and service. The model of transportation and the management of subsequent logistics remain as crucial to success as the efficient production of the material itself.

Vulcan

Figure 4.1 Attractively landscaped quarry entrance

Luck Companies

Figure 4.2 Attractively landscaped quarry entrance with berm

Figure 5.3 Graphical EMS model

Volvo Construction Equipment

Figure 10.3 Mid-Atlantic Region Dump Truck

Volvo Construction Equipment

Figure 10.4 Super Dump Truck

Volvo Construction Equipment

Figure 10.5 Transfer Dump Truck

Volvo Construction Equipment

Figure 10.6 Truck and Pup

Volvo Construction Equipment

Figure 10.7 Double-trailer Load-out

L.G. Everist, Inc.

Figure 10.8 End Dump Semi-truck

Volvo Construction Equipment

Figure 10.9 Belly Dump Semi-truck

L.G. Everist, Inc.

Figure 10.10 Double Trailer Side Dump "Train"

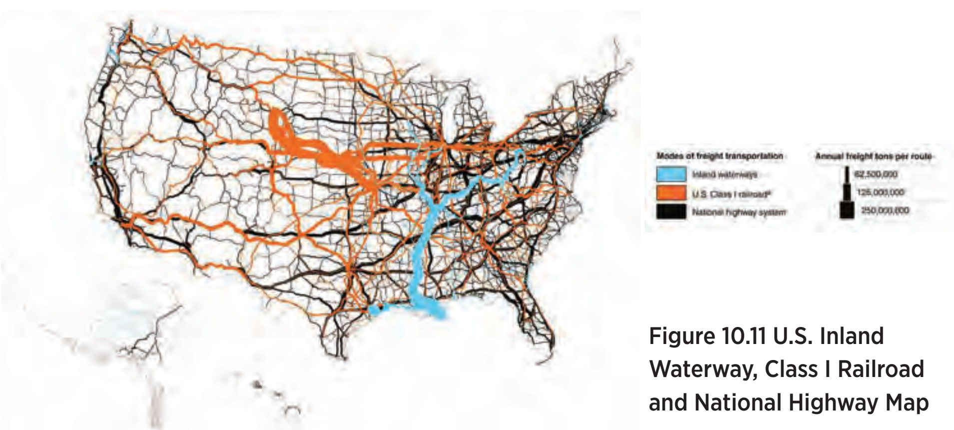


Figure 10.11 U.S. Inland Waterway, Class I Railroad and National Highway Map

This image excerpted from a U.S. Department of Transportation, Government Accountability Office Report, GAO-11-134 Freight Transportation. Highways: U.S. Department of Transportation, Federal Highway Administration, Freight Analysis Framework, Version 3.1.2010. Rail: Based on Surface Transportation Board, Annual Carload Waybill Sample and Rail Freight Flow Assignments done by Oak Ridge National laboratory. Inland Waterways: U.S. Army Corps of Engineers (Corps), Annual Vessel Operating Activity and Lock Performance Monitoring System Data, as processed for Corps by the Tennessee Valley Authority; and Corps, Institute for Water Resources, Waterborne Foreign Trade Data, Water Flow Assignments done by Oak Ridge National Laboratory.

L.G. Everist, Inc.

Figure 10.12 Typical Rail Terminal

Norfolk Southern Corp.

Figure 10.13 Hopper Car

Tealinc, Ltd.

Figure 10.14 Gondola Car

Herzog Companies Inc.

Figure 10.15 Ballast Car

Knife River

Figure 10.17 Overhead Trestle Unload

Wilson Manufacturing & Design, Inc.

Figure 10.18 Self-propelled Rock Unloader

L.G. Everist, Inc.

Figure 10.19 Ballast Rock Load-out

Martin Marietta

Figure 10.20 Granite Canyon Quarry, Overhead Bin Load-out


Knife River.

Figure 10.21 High-Volume Conveyor Loading Unit Train


Norfolk Southern Corp.

Figure 10.22 Multiple Overhead Bin Load-out


Albert Frei and Sons

Figure 10.24 Overhead Bin Load-out


Norfolk Southern Corp.

Figure 10.26 Unload/Reload Site

Penta-Ocean Construction Co. Ltd.

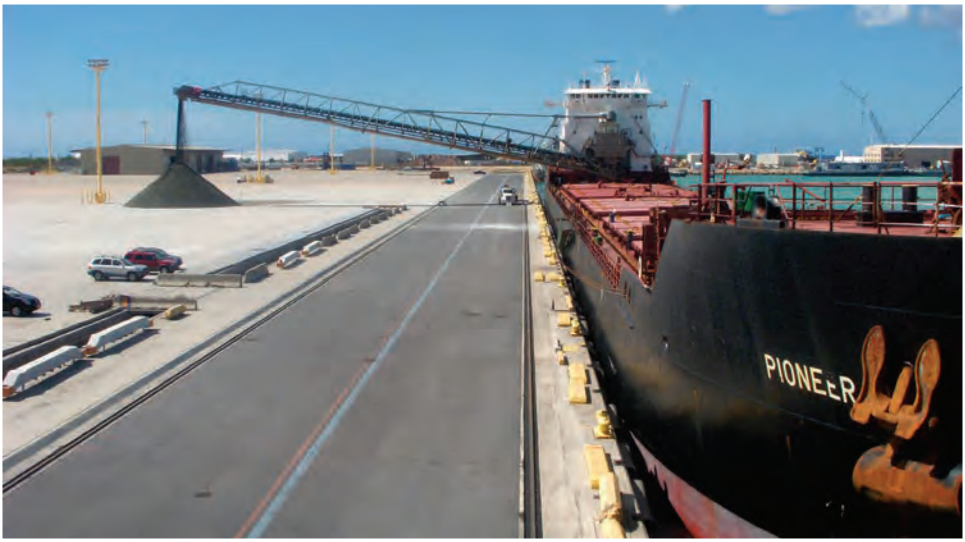
Figure 10.27 Pusher Tug “Jupiter 5” and Hopper Barge “PB-33”

Superior Industries LLC

Figure 10.28 Flat Deck Barge Loading

CSL International

Figure 10.29 Self-unloader



Polaris Minerals Corporation

Figure 10.30 Shore-based Bulk Aggregates Carrier Unloading Directly into Stockpile

Superior Industries LLC

Figure 10.32 High-Volume Ship Unload–Telescopic

Polaris Minerals Corporation

Figure 10.34 Barge Litering Operation at Anchorage

Polaris Minerals Corporation

Figure 10.35 Barge Litering Operation: Off-loading into small hopper barges while at anchor in San Francisco Bay

Figure 12.2 Aggregates Particles, Uniform Sized (Poorly Graded) and Rounded or Soft

Figure 12.3 Aggregates Particles, Many Sizes (Well-Graded) and Angular or “Sharp”

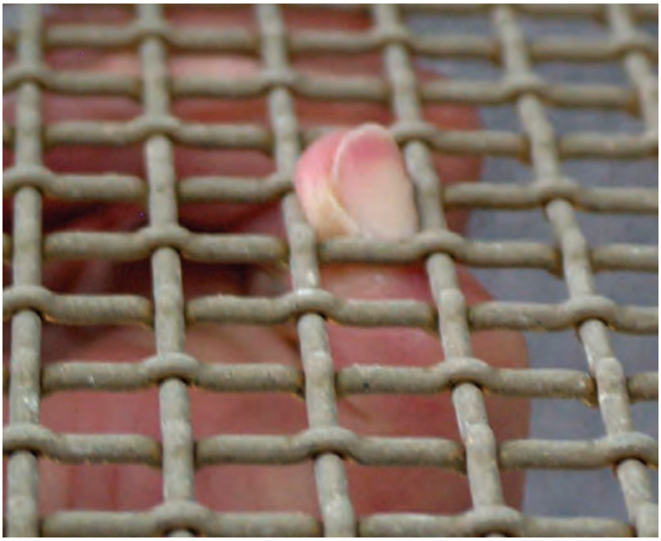


Figure 12.4 ASTM Sieve with Finger for Scale

Figure 12.5 Hydrometer for Particle Sizes Finer than No. 200 Sieve

Figure 12.7 Fine Rounded Sand at “Angle of Repose”

Figure 12.17 Completed MSE Retaining Wall Along Highway in New Mexico

Figure 12.18 Typical Soil used for MSE Wall Backfill

Figure 12.19 Construction of MSE Wall

Figure 12.20 Placing Reinforcements in MSE Wall

Figure 12.21 Installation of Pre-cast MSE Wall Faces Using Heavy Equipment

Figure 12.24 Photograph of Vesicular Basalt from Ambrosia Lake Near Grants, New Mexico

Figure 12.25 Fractured Dye Test Performed on Metamorphic Siltstone Obtained from a Quarry Near Gunnison, Colorado (Red Dye and Powder Applied to Rock to Reveal Hairline Fractures)

Courtesy of the International Erosion Control Association

Figure 12.28 Photograph of Gabion Mattress Lining Installation to Prevent Erosion

Courtesy of the International Erosion Control Association

Courtesy of Eurogabions Solutions

Figure 12.31 Photograph of Gabion Sacks

Figure 12.30 Gabion Mattress Lining Installation Along Slope to Prevent Erosion

Figure 12.32 Photograph of Load Test for Geopier® with Uplift Anchors

Figure 12.33 Patented Tamper by Geopier® Foundation Company

Figure 12.34 Steel Auger used by Geopier® Foundation Company

Figure 12.35 Cuttings Removed from Cavity Using Auger by Geopier® Foundation Company

Figure 12.36 Completely Installed Rammed Aggregates Pier Element with Uplift Anchors Installation by Geopier® Foundation Company

Figure 14.3 Slip Form Paver

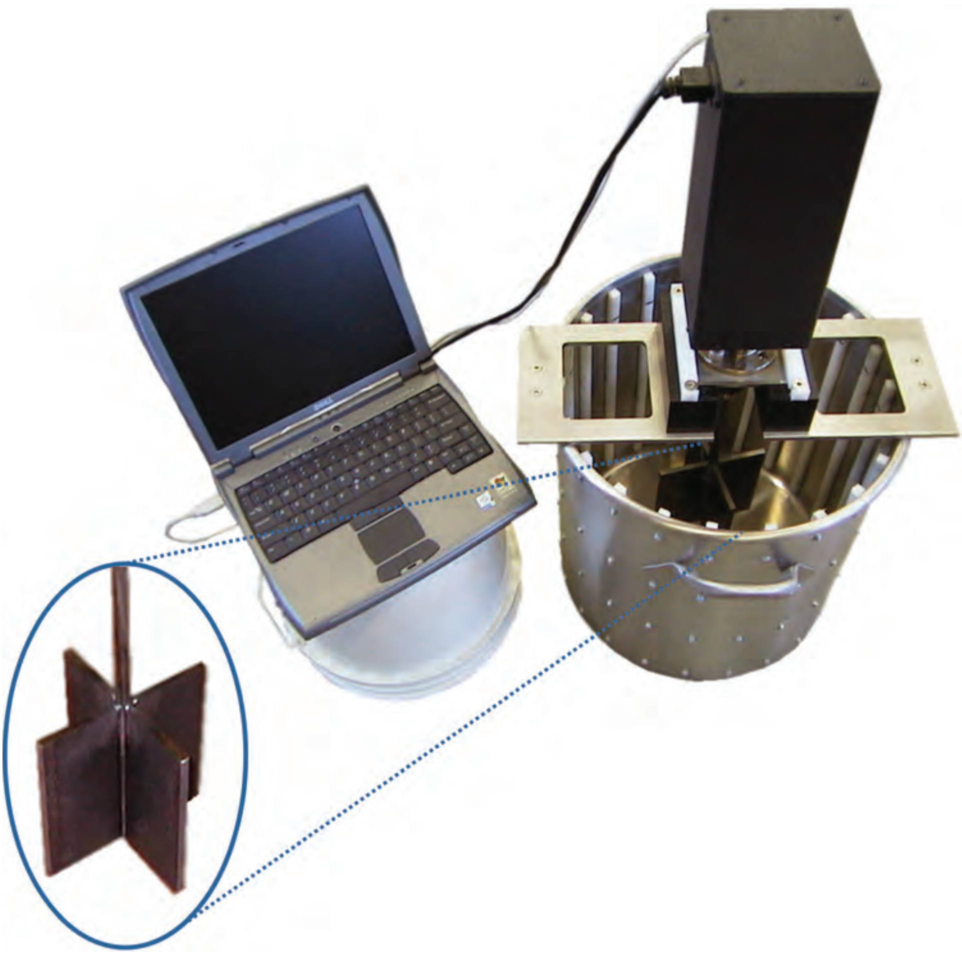


Figure 14.4 ICAR Rheometer

Figure 15.4 Marshall Hammer

Figure 15.5 Marshall Stability and Flow Machine

Figure 15.6 Superpave Gyratory Compactor

Figure 15.9 Hamburg Wheel-Tracking Device

Figure 15.10 Asphalt Pavement Analyzer

Figure 18.5 Sampling from a Conveyor Belt

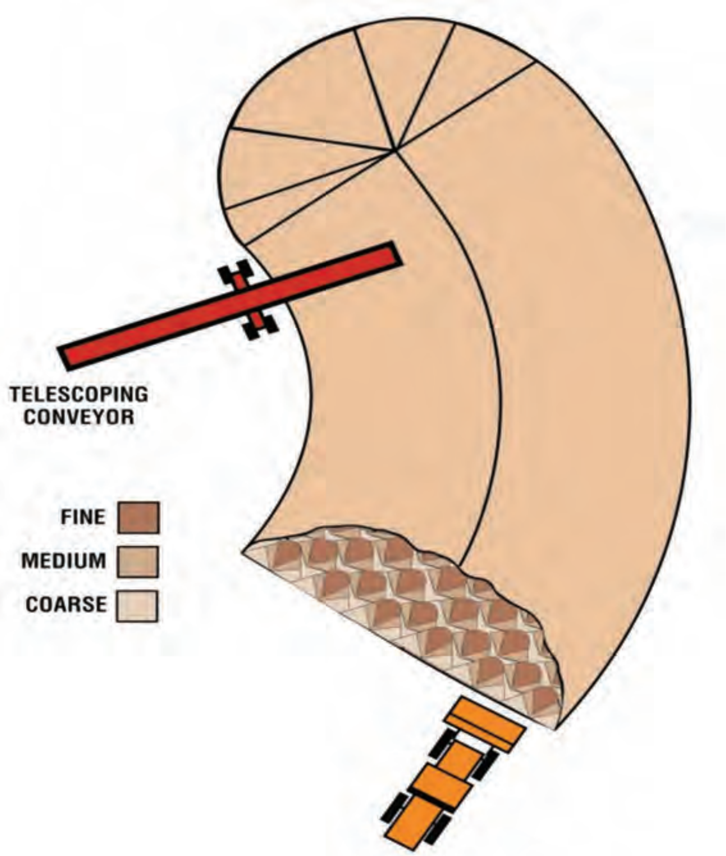


Figure 18.10 Telescoping Radial Stacker

Chapter 11

Aggregates as a Structural Product

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David Fowler
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Sam Johnsons
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Don Powell
Carlos Santamarina
Erol Tutumluer

First Edition
Marshall Thompson

11.1 Introduction

Aggregates are used in many horizontal layer structural applications such as in pavement construction. This chapter describes aggregates layer functions and aggregates strength and modulus properties and the factors affecting them. Typical aggregates specifications also are presented.

The largest uses of aggregates as structural products are in pavements for highways, airfields, parking lots, storage areas and as ballast or subtlest layers in railroad track structures. Other uses in horizontal construction are working platforms over weak layers, pedestrian walkways, bicycle paths and similar types of facilities. Aggregates products also are used in such geotechnical structural applications as stone columns and reinforced soil construction. The functions that aggregates layers provide vary greatly, depending on the specific application.

11.2 Aggregates Layer Functions

Pavements

Definitions: The *base course* of a pavement lies immediately below the pavement surface and provides support for it. The base may consist of either a high quality, unstabilized aggregates layer or an aggregates layer stabilized with asphalt, cement or lime. The *subbase*, if present, is located below the base and serves a similar function as the base. Frequently the subbase is composed of materials of slightly lower quality than the base. For best performance both the base and subbase should consist of a well-graded, non-plastic crushed aggregates having a maximum size no less than 1.5 inches and contain less than 8 percent fines. The base should be compacted in the field to 100 percent of AASHTO T-180 density.

Functions: The major structural function of an aggregates layer serving as a pavement base course or sublease is to spread the stresses (i.e., decrease the stresses with depth) applied to the pavement surface by traffic loading. These stresses must be reduced to levels that do not overstress the underlying base, sublease or subgrade. Overstressing either bound materials, such as asphalt concrete, or unbound aggregates or soil can produce unacceptable levels of *resilient* pavement deflections under moving wheel loads or accumulate excessive amounts of *permanent deformation* (rutting). *Resilient deflections* are pavement deflections that are recovered after the load is removed in contrast to *permanent deformations*, which are not recovered but gradually increase with applied numbers of wheel loadings.

If traffic loading is directly applied to the aggregates layer, or if only a thin, non-structural layer such as a surface treatment is utilized, the uppermost aggregates layer must possess sufficient strength and rutting resistance to minimize bearing capacity and rutting failure within the layer. For aggregates surfaced roads, the aggregates layer also must possess good wear resistance to minimize the loss of material (*attrition*) under traffic.

Use of a granular layer also provides other positive benefits including making construction over the layer easier, controlling pumping, reducing frost action, improving drainage of surface or subsurface water and controlling volume change in the surged when expansive soils are present.

Track Structure Applications

The *ballast layer* is the uppermost aggregates layer in a railroad track structure and is located immediately beneath and surrounding the ties. The layer underlying the ballast is called the *subballast*. Subballast layers are not always utilized in track construction.

Ballast: Peckover[1] states, "Good ballast material provides elastic support and anchorage for track with a minimum of maintenance." The functions of ballast as described by Hay[2] and Peckover[3] are summarized as follows:

1. Transmit the imposed loadings uniformly to the roadbed (subgrade soil) at a stress tolerable for the particular material in the roadbed.
2. Provide uniform support for the ties with the necessary degree of elasticity and resilience to absorb vibrations and shock.
3. Anchor the track in place and resist vertical, lateral and longitudinal movement.
4. Provide immediate free drainage and prevent the growth of vegetation.
5. Resist aggregates degradation due to physical forces exerted by traffic and maintenance equipment and due to environmental factors such as freeze/thaw, wet/dry, etc.
6. Facilitate maintenance operations such as the correction of vertical track surface irregularities, horizontal line irregularities and ballast cleaning operations.
7. Resist fouling, which is the accumulation of fines, and cementing, which is evidenced by the apparent bonding together of aggregates particles.
8. Minimize climatic influences such as frost heave, swelling, etc., in the roadbed.

Subballast: According to Spang,[4] the functions of the subballast layer are:

1. Distribution of ballast pressure and traffic loads.
2. Damping of vibrations.
3. Filtering of the layers above and below the subballast.
4. Protection of the subgrade or foundation layer against damage caused by frost.
5. Reducing rainwater penetration into the subgrade.

The aggregates layer fulfills similar functions in many of the typical structural applications such as pavements and track structures. A broad range of aggregates possessing diverse properties and characteristics are available to meet the various application requirements.

11.3 Aggregates Properties

Aggregates specifications for various uses generally include sections relating to gradation, degree of crushing, plasticity (liquid limit and plasticity index), durability and soundness, and abrasion resistance. Some specifications include a strength requirement such as a minimum California Bearing Ratio (CBR) value. A detailed specification for unbound aggregates base is given in Chapter 15.

Gradation: Particle gradation, which is the distribution of the various particle size fractions in the aggregates, is an important property. Standard aggregates gradations following the American Society for Testing and Materials (AST) specification AST D 448 are presented in Table 11.1. Frequently, these standard gradations are incorporated into a more detailed specification for a specific application, such as a railroad ballast. For example, AST No. 4 gradation is the equivalent of American Railway Engineering Association (AREA) No. 4 ballast gradation.

Talbot Equation: Well-graded aggregates have a good representation of all particle size fractions from the maximum size through the smaller sizes. The following approximate gradation equation, referred to as the Talbot Equation, is frequently used as an aid in selecting a suitable gradation for structural applications:

$$P = \left(\frac{d}{D}\right)^n \cdot 100 \qquad (2\text{-}2)$$

where

P = Percent passing sieve size "d" expressed in inches
d = Sieve size opening expressed in inches. for which the percent passin (P) is applicable
D = Maximum aggregates size (in.)
n = An empirical gradation exponent

The coefficient "n" is generally taken to be ⅓ to ½ for well-graded materials; frequently n = 0.45 is used. As the coefficient "n" increases, the percent passing sieve size "d" decreases.

Uniformity: The *uniformity coefficient* Cu is employed to quantify how uniform or well graded an aggregates is:

$$C_u = \frac{D_{60}}{D_{10}}$$

where

C_u = Uniformity coefficient
D_{10} = Grain size for which 10% of the particles by weight are smaller
D_{60} = Grain size for which 60% of the particles by weight are smaller

Table 11.1 Standard Sizes of Processed Aggregate (ASTM Standard Specification D448)

Size Number	Nominal Size, Square Openings	Amounts Finer than Each Laboratory Sieve (Square Openings), weight percent														
		4 in. (100 mm)	3½ in. (90 mm)	3 in. (75 mm)	2½ in. (63 mm)	2 in. (50 mm)	1½ in. (37.5 mm)	1 in. (25.0 mm)	¾ in. (19.0 mm)	½ in. (12.5 mm)	⅜ in. (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 50 (300-μm)	No. 100 (150-μm)
1	3½ to 1½ in. (90 to 37.5 mm)	100	90 to 100	...	25 to 60	...	0 to 15	...	0 to 5	...	...	...	...	...	...	...
2	2½ to 1½ in. (63 to 37.5 mm)	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...	...	...	...
24	2½ to ¾ in. (63 to 19.0 mm)	...	...	100	90 to 100	...	25 to 60	...	0 to 10	0 to 5	...	...	...	...	...	...
3	2 to 1 in. (50 to 25.0 mm)	...	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...	...	...
357	2 in. to No. 4 (50 to 4.75 mm)	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	...	0 to 5	...	...	...	...
4	1½ to ¾ in. (37.5 to 19.0 mm)	...	...	...	...	100	90 to 100	20 to 55	0 to 15	...	0 to 5	...	...	...	...	...
467	1½ in. to No. 4 (37.5 to 4.75 mm)	...	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	0 to 5	...	...	...	...
5	1 to ½ in. (25.0 to 12.5 mm)	...	...	...	...	...	100	90 to 100	20 to 55	0 to 10	0 to 5	...	...	...	...	...
56	1 to ⅜ in. (25.0 to 9.5 mm)	...	...	...	...	...	100	90 to 100	40 to 85	10 to 40	0 to 15	0 to 5	...	...	...	...
57	1 in. to No. 4 (25.0 to 4.75 mm)	...	...	...	...	...	100	95 to 100	...	25 to 60	...	0 to 10	0 to 5	...	...	...
6	¾ to ⅜ in. (19.0 to 9.5 mm)	...	...	...	...	...	...	100	90 to 100	20 to 55	0 to 15	0 to 5	...	...	...	...
67	¾ in. to No. 4 (19.0 to 4.75 mm)	...	...	...	...	...	...	100	90 to 100	...	20 to 55	0 to 10	0 to 5	...	...	...
68	¾ in. to No. 8 (19.0 to 2.36 mm)	...	...	...	...	...	...	100	90 to 100	...	30 to 65	5 to 25	0 to 10	0 to 5	...	...
7	½ in. to No. 4 (12.5 to 4.75 mm)	...	...	...	...	...	...	...	100	90 to 100	40 to 70	0 to 15	0 to 5	...	...	...
78	½ in. to No. 8 (12.5 to 2.36 mm)	...	...	...	...	...	...	...	100	90 to 100	40 to 75	5 to 25	0 to 10	0 to 5	...	...
8	⅜ in. to No. 8 (9.5 to 2.36 mm)	...	...	...	...	...	...	...	...	100	85 to 100	10 to 30	0 to 10	0 to 5	...	...
89	⅜ in. to No. 16 (9.5 to 1.18 mm)	...	...	...	...	...	...	...	...	100	90 to 100	20 to 55	5 to 30	0 to 10	0 to 5	...
9	No. 4 to No. 16 (4.75 to 1.18 mm)	...	...	...	...	...	...	...	...	...	100	85 to 100	10 to 40	0 to 10	0 to 5	...
10	No. 4 to 0[a] (4.75 mm)	...	...	...	...	...	...	...	...	...	100	85 to 100	...	...	...	10 to 30

[a]Screenings.

Well-graded aggregates generally have large C_u values indicating a considerable range of particle sizes. For a Talbot based gradation following equation 11-1, the uniformity coefficient Cu is equal to $6^{1/n}$. Thus for n = 0.5, Cu is 36. A C_u less than about 4 indicates a uniform gradation which can present placement and compaction problems.

Dust Ratio: The *dust ratio* is another gradation parameter often used in base and subbase gradation requirements. The dust ratio is defined as the percent passing the No. 200 sieve divided by the percent passing the No. 40 sieve. The desired value is generally around ⅔. Atterberg limit tests are conducted on the minus No. 40 sieve size fraction.

Pavements: Typical aggregates specifications for pavement surface, base and subbase courses are presented in AASHTO M 147, ASTM D 2940 and ASTM D 1241 specifications, which are summarized in Chapter 15. State transportation organizations and other specifying agencies often have similar specifications that frequently have been slightly modified to accommodate local conditions. AASHTO M 147 and ASTM D 1241 specifications have different liquid limit and plasticity index requirements for surface compared to base and sub- base materials. For non-stabilized aggregates surface courses, AASHTO M 147 and ASTM D 1241 allow a higher liquid limit (35 percent maximum) and a larger plasticity index, from 4 to 9 percent. For aggregates base and subbase materials, AASHTO specifications allow a maximum liquid limit of 25 percent and a maximum plasticity index of 6 percent. For best performance, however, the aggregates base should be non-plastic.

Railroads: The American Railway Engineering Association (AREA) has developed ballast and subtlest specifications for track structure construction. The specification and accompanying commentary is presented in the revised 1986 edition of the Manual for Railway Engineering.[5] This major revision of the manual, the first in over 40 years, recognizes the significant changes that have occurred in railroad wheel loadings and modern railroad operating conditions. The summary accompanying the AREA specification states:

"The AREA Ballast Specification is intended as a guideline and cannot cover all of the requirements necessary for the full appraisal of the in-track performance of a ballast material. It is not possible to incorporate into the laboratory tests those field factors, which include geographical and climatic conditions, load variations, subgrade conditions and other conditions, which will actually determine the total in-track performance of a ballast material. Generally the revised specifications have established material standards and test requirements which will provide more efficient ballast materials commensurate with current roadbed structure and performance requirements."

The AREA ballast specification includes recommended limiting values for various properties as shown in Table 11.2 and recommended ballast gradations as shown in Table 11.3. Railway ballast materials have a uniform gradation, large maximum size and permit little, if any, minus No. 4 sieve size material to be present.

Table 11.2 Recommended Limiting Values of Testing for Ballast Material

Property	Granite	Traprock	Quartzite	Limestone	Dolomitic Limestone	Blast Furnace Slag	Steel Furnace Slag	ASTM Test
Percent Material Passing No. 200 Sieve	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	C 117
Bulk Specific Gravity[(2)]	2.60	2.60	2.60	2.60	2.65	2.30	2.90	C 127
Absorption Percent	1.0	1.0	1.0	2.0	2.0	5.0	2.0	C 127
Clay Lumps & Friable Particles	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	C 142
Degradation	35%	25%	30%	30%	30%	40%	30%	(1)
Soundness (Sodium Sulfate) 5 Cycles	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	C 88
Flat and/or Elongated Particles	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	USACE CRD-C 119

Note: 1. Materials having gradations containing particles retained on the 1 in. sieve shall be tested by ASTM C535. Materials having gradations with 100% passing the 1 in. sieve shall be tested by ASTM C131.
2. The limit for bulk specific gravity is a minimum value. Limits for the remainder of the tests are maximum values.

Table 11.3 Recommended Ballast Gradations

Size No.	Nominal Square Opening	PERCENT PASSING 3 in.	2½ in.	2 in.	1½ in.	1 in.	¾ in.	½ in.	⅜ in.	No. 4	No. 8
24	2½ in.:¾ in.	100	90:100		25:60		0:10	0:5			
25	2½ in.:⅜ in.	100	80:100	60:85	50:70	25:50		5:20	0:10	0:3	
3	2 in.:1 in.		100	95:100	35:70	0:15		0:5			
4A	2 in.:¾ in.		100	90:100	60:90	10:35	0:10		0:3		
4	1½ in.:¾ in.			100	90:100	20:55	0:15		0:5		
5	1 in.:⅜ in.				100	90:100	40:75	15:35	0:15	0:5	
57	1 in.:No. 4				100	95:100		25:60		0:10	0:5

Note: 1. Gradation Numbers 24, 25, 3, 4-A, and 4 are main line ballast materials. Gradation Numbers 5 and 57 are yard ballast materials.

Degradation Resistance: A particularly important and demanding requirement for railway ballast is high resistance to aggregates break- down and degradation under repeated train traffic loading. In most ballast gradations, little if any material passes the No. 4 sieve. The ballast may degrade under traffic and generate minus No. 4 material, as illustrated in Figure 11.1. Other sources of fines are surface contamination and intrusion of subgrade into the open-graded ballast. The major source of ballast fines is aggregates degradation under trafficking. *Dirty ballast* has greater than 15 to 20 percent of its particles smaller than the No. 4 sieve. Dirty ballast, when wet and subjected to heavy repeated loading, expels a slurry of fines and water from the aggregates. This phenomenon is called *pumping* and can lead to excessive settlement.

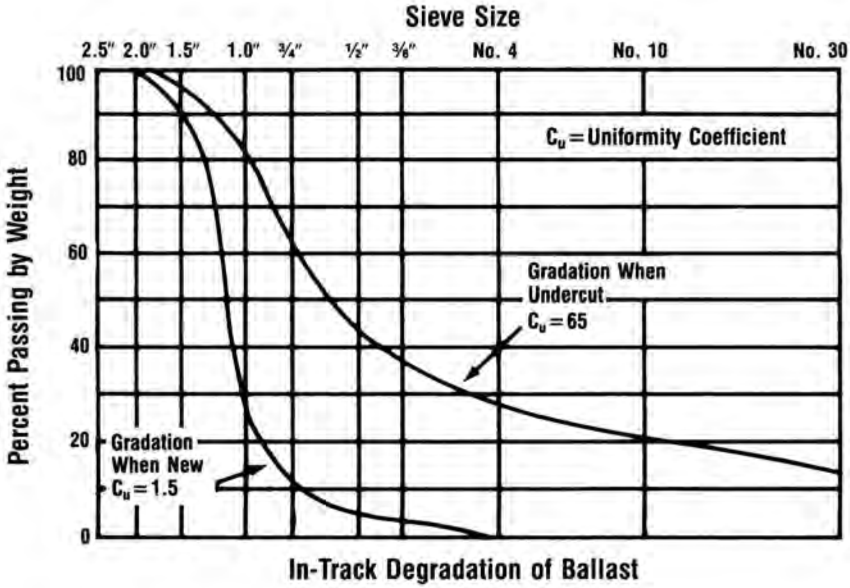


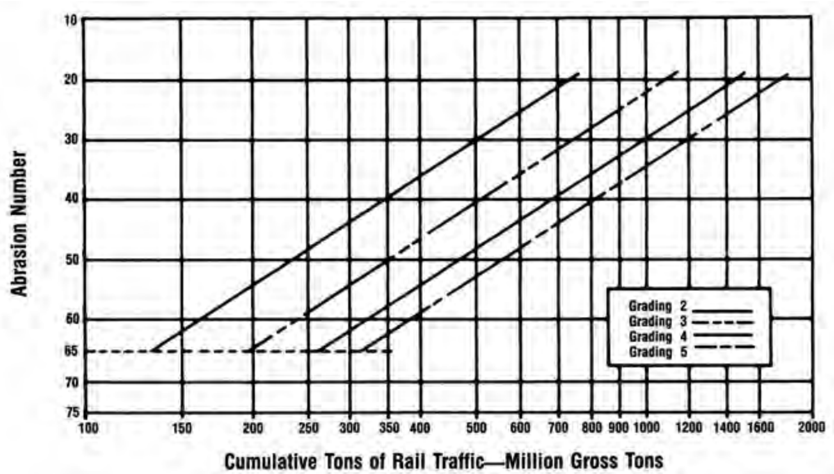
Figure 11.1 Typical degradation of railroad ballast under traffic.

Abrasion Number: Recent studies[7,8] indicate that the ballast *abrasion number* is a good indicator of potential ballast degradation and can be used to predict ballast performance. The *abrasion number* is defined as the Los Angeles abrasion value + (5xMill abrasion value). The *Mill Abrasion Test* is described in Chapter 3. Figure 11.2 relates abrasion number to ballast life and was developed by the Canadian Pacific Railroad. The Canadian Pacific Railroad's Track Ballast Standards associated with the gradations used in the figures are also shown in Figure 11.2. These performance concepts have been used to develop a *ballast renewal model*[9] for predicting ballast life in terms of millions of gross tons of traffic. The end of the ballast life is considered to be reached when voids in the ballast become filled due to fouling.

Ballast degradation considerations are more critical for concrete than for wood tie installations. Concrete tie track sections, carbonate materials, slags and materials having a No. 57 ballast gradation (refer to Table 11.1) are excluded from use by current AREA specifications.

The AREA subballast specification allows a variety of materials to be used: "Materials used as subballast and most commonly available are those materials used in highway construction including crushed stone, natural or crushed gravels, natural or manufactured sand, crushed slag or a homogenous mixture of some of these materials. Other natural materials such as sand/clay/gravels and clay/gravels or on site materials may be used provided proper engineering standards and specifications are defined by the individual railway companies."

The AREA subballast specification is considerably less stringent than the ballast specification. Although various properties and test methods are referenced, the subballast specification does not contain specific numerical limits and requirements.



Note: Developed for tangent track with 7 in. of ballast below tie. A small amount of contamination from outside sources has been taken into consideration.

Caution: Excessive handling of ballast materials in the upper range of abrasion numbers may generate fines that will reduce the applicable cumulative tons of rail traffic.

Figure 11.2 Typical degradation of railroad ballast under traffic.

Track Classification	Primary Main Line CWR	Primary Main Line Jointed	Secondary Main Line	Branch Line Important	Branch Line Minor
Stability–minimum allowable values given					
Bulk Specific Gravity	2.60	2.60	2.60	2.60	2.60
Fractured Particles–percent					
Ballast Grading					
2	–	70	60	60	60
3	80	75	65	60	60
4	90	85	75	65	65
5	100	–	–	–	–
Weathering–maximum allowable values given					
Magnesium Soundness	1	1.5	3	3	3
Absorption	0.50	0.75	1	1	1
Abrasion					
Los Angeles Abrasion	shall be less than 45				
Mill Abrasion	shall be less than 9				
Abrasion Number	shall be less than 65; also shall be less than Abrasion Number for the cumulative tons of rail traffic for a 20-year period, should be less than Abrasion Number for the cumulative tons of rail traffic for a 30-year period.				

Ballast Grading	Maximum Size (in.)	2½"	2"	1½"	1"	¾"	½"	⅜"	No. 4	No. 200
		Percent by Weight Finer than Specified Sieve								
2	2	–	100	90-100	70-90	50-70	25-45	10-25	0-3	0-2
3	2	–	100	90-100	70-90	30-50	0-20	0-5	0-3	0-2
4	2	–	100	90-100	20-55	0-5	–	–	0-3	0-2
5	2½	100	90-100	35-70	0-5	–	–	–	0-3	0-2

Ballast gradings 2 and 3 shall be used for crushed gravel.

Ballast grading 4 shall be used for crushed gravel, crushed rock or slag.

Ballast grading 5 shall be used for crushed rock or slag.

Figure 11.2b Track ballast standards.

Abrasion Number

The abrasion number is used to characterize ballast degradation potential and to predict ballast life by some railroads. The abrasion number is a numeric index equal to the L.A. degradation value plus five times the mill abrasion value. These tests are described in Section 3.7 of Chapter 3 and also in Section 11.3, Chapter 11 of the Handbook. Canadian Pacific Railroad standards require a mill abrasion value less than 9 for ballast aggregates. Most quality ballast aggregates meet this requirement. Note in Figure 11.2 of the Handbook that the "Cumulative Tons of Rail Traffic," given on the x-axis of the graph, is sensitive to the value of the abrasion number.

Chrismer[1], with the Association of American Railroads (AAR), presented a comprehensive ballast maintenance model (BALLAST2). He states that:

> *"The model predicts the timing of required ballast maintenance based on the predicted rate of track settlement and associated roughness." He further indicates: "The ballast life is defined primarily in terms of breakdown from traffic loading which causes the ballast voids to become filled."*

Chrismer also cites a field study[2] of 35 track sites throughout the U.S. that showed approximately 73 percent of the fouling particles (i.e., particles less than ⅜ inch in size) that reduces the strength and permeability of the ballast were derived from ballast degradation. Chrismer's BALLAST2 model, similar to a model developed by the Canadian Pacific Railroad, utilizes the abrasion number to consider ballast material quality. He presents a caveat:

> *"Although the A_N (Abrasion Number) has been related with some success to ballast life, other ballast properties not reflected in this measure are as important. For example, an experienced petrographer may examine the rock sample further and determine that it may be prone to chemical weathering or some other mechanism which is not evaluated in the Mill Abrasion or L.A. Abrasion tests which determine the AN value. For this reason, a petrographic evaluation is always recommended."*

A small change in the mill abrasion value is greatly magnified (by a factor of five) in calculating the abrasion number. Thus, the repeatability and reproducibility of the mill abrasion test is of considerable significance. The American Railway Engineering Association's (AREA) Committee No. 1/Sub-Committee No. 2 - Ballast considered this issue in an extensive round robin type study that included seven independent laboratories and six ballast materials. Considerable variability was exhibited in test results. This finding prompted the committee to conclude that the repeatability of the mill abrasion test is not an acceptable test for accepting or rejecting ballast materials.

The mill abrasion test equipment, procedures and techniques need to be refined and/or modified to increase reliability and reproducibility. An alternative is to develop an alternative test procedure(s) for evaluating aggregates degradation potential. No particularly promising test procedures exist at this time.

11.4 Strength and Deformation Properties of Aggregates

1. Use more up-to-date and realistic mixtures and gradations.
2. Provide typical confining pressures reflecting known field conditions.
3. Show realistic field scenarios, which depict, for example, attempting T-180 compaction over poor soils with granular embankments (C.A. Sanders).

Strength and stress/strain relations are important aggregates properties. Since many aggregates do not possess cohesion, methods are required that provide confinement in order to hold the specimens together during testing.

Triaxial Testing

Slow Triaxial Shear Test: Triaxial testing is a fundamental testing procedure that is useful for characterizing aggregates base and other materials. A test specimen is prepared at a target density and moisture content and is then encased in a membrane. The specimen is subjected to a constant all-around confining pressure, s_3, and then loaded under an increasing axial stress until failure. Since the axial stress is in addition to the confining stress already on the specimen, it is called the deviator stress, s_1 - s_3. The total axial stress is called s_1. Usually three triaxial tests are conducted over a range of confining pressure levels representative of probable in-service conditions. Confining pressures used typically vary from 3 to 40 psi. Axial strain rates used in triaxial testing typically vary from 0.5 inch per inch to 2 inches per inch per minute, which are considered slow loading conditions. Strain, which is actually unitless, is often given as inch per inches. Therefore, strain expressed as a percent involves multiplying the strain by 100. Hence, a strain rate of 2 percent per minute means a strain of 0.02 inch per inches is applied to the specimen in one minute.

Rapid Triaxial Shear Test: Vehicles usually move across a pavement very quickly. Therefore, a triaxial shear test performed at a rapid shearing rate is more representative of usual loading conditions than the conventional slow triaxial shear test. A triaxial shear test performed at a strain rate of about 10 to 17 inches per inch per second is therefore defined as the *Illinois rapid shear test*. *Axial strain* is defined as axial deformation divided by the distance over which the deformation is measured.

Triaxial Data Reduction: Triaxial test data is interpreted to determine the cohesion (c) and angle of internal friction (ϕ) of the material tested. The parameters c and ϕ define the shear strength of the material, which is given by the Mohr-Coulomb equation:

$$s = c + \sigma \tan \phi \quad (11\text{-}3)$$

where

s = Shear strength
c = Cohesion
σ = Normal effective stress on specimen failure plane
ϕ = Angle of internal friction

Usually, a constant angle of internal friction is assumed to exist over the range of confining pressures tested. For a constant value of ϕ, the principal stress at failure ($\sigma_1 = \sigma_3$ + maximum applied axial deviator stress, $\sigma_1 - \sigma_3$) can be plotted against the confining pressure (σ_3) as shown in Figure 11.3. The axial stress σ_1 can be expressed as a linear function of σ_3:

$$\sigma_1 = a + b\,\sigma_3 \quad (11\text{-}4)$$

where a is the intercept and b the slope as shown in Figure 11.3. Knowing the constants a and b determined from the triaxial test data, then the cohesion (c) and the angle of internal friction (ϕ) can be calculated:

$$c = a/\ (2b0.5) \quad (11\text{-}5)$$

$$\phi = \sin\text{-}1\ [(b - 1)\ /\ (b + 1)] \quad (11\text{-}6)$$

where all terms have been previously described. The relation between σ_1 and σ_3 at failure can be expressed as:

$$\sigma_1 = \sigma_3\ N\phi,\ + 2c\ N\phi 0.5 \quad (11\text{-}7)$$

where

$N\phi$, = tan2 (45 + ϕ/2))

For a material that has no cohesion (c):

$$\sigma_1/\sigma_3 = \tan 2\ (45 + (\phi/2)) \quad (11\text{-}8)$$

Maximum principle stress ratios at failure (σ_1/(σ_3) for cohesionless materials for a range of angles of internal friction are:

Friction Angle, ϕ (degrees)	Principle Stress Ratio (σ_1/(σ_3)
30	3.0
40	4.6
50	7.5
60	13.9

The above data clearly show that a small increase in the angle of internal friction ϕ causes a large increase in the failure stress ratio, σ_1/σ_3, with this ratio becoming disproportionately greater as f increases. The angle of internal friction tends to be larger at low levels of confining pressure and decreases slightly as the confining pressure undergoes a moderate increase. The angle of internal friction also increases with an increase in density, particularly at low confining pressures. The effects of confining pressure and density on "f" are illustrated in Figure 11.4 for an open-graded AREA No. 4 ballast aggregate having 7.5 percent stone screenings added to it.

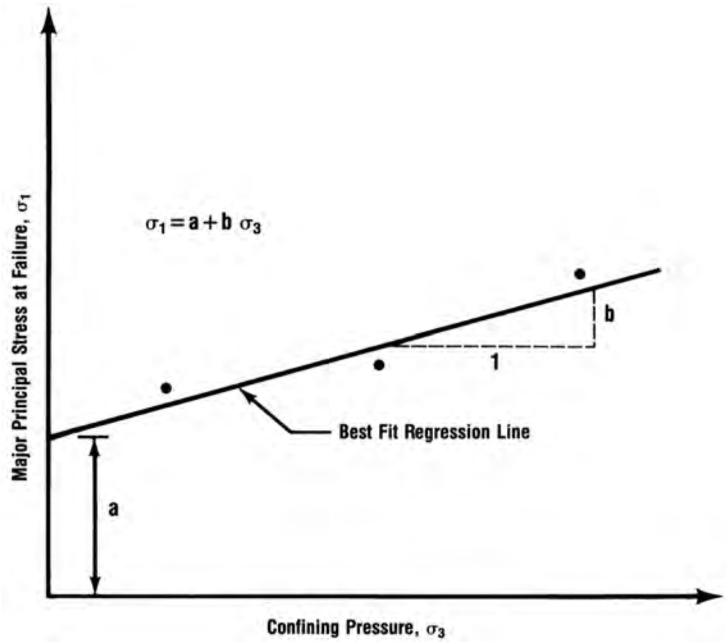


Figure 11.3 Triaxial test results plotting major principal stress at failure as a function of confirming pressure.

Triaxial Classification of Base Aggregates: In ASTM D 3397, which was withdrawn in 1989, a procedure is presented for Triaxial Classification of Base Materials, Soils and Soil Mixtures. The chart given in ASTM D 3397 is shown in Figure 11.5 and can be used to classify material on the basis of shear strength.

Stress-strain Relationships: Axial load-deformation data from a triaxial test performed on a given gradation of material can be reduced to develop a relationship between deviator stress (σ_1-σ_3) and axial strain for each confining pressure in the test. This relationship is often referred to as a *stress/strain curve*. The *modulus of elasticity* (E), also referred to as the modulus of deformation, is the slope of a plot of deviator stress as a function of axial strain. The stress-strain relationship is generally not linear but curved, as illustrated in Figure 11.6. The data shown in Figure 11.6 are from a rapid triaxial test performed on a well-graded gravel.

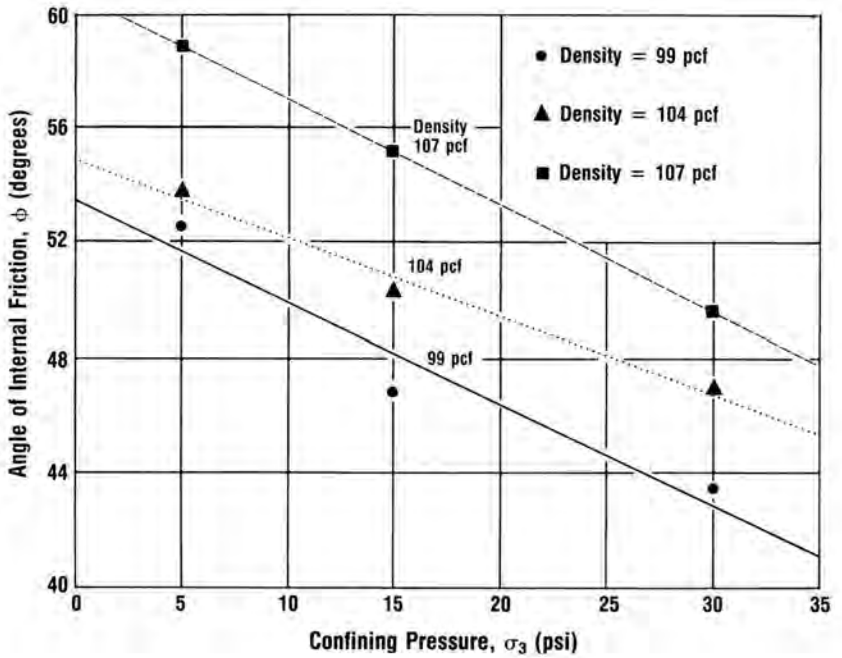


Figure 11.4 Effects of confining pressure and density on angle of internal friction.

The *initial tangent modulus* is the slope of the initial linear stage of the stress/strain curve as shown in Figure 11.6. An alternative is to determine a secant modulus for a selected stress level generally about 50 to 75 percent of the failure shear strength of the material or at a specified strain level. The *secant modulus* is determined by dividing the observed stress by the strain at the selected percent of the failure shear strength. Hence, the secant modulus represents the slope of a chord through the selected point and the origin of the stress/strain curve, as illustrated in Figure 11.6.

Factors Influencing Shear Strength: Factors influencing the shear strength of an aggregates include gradation, density, plasticity index, particle geometric characteristics (shape, angularity, surface texture) and moisture content. Methods for measuring these characteristics are described in Chapter 3.

National Crushed Stone Association Study: The National Crushed Stone Association (predecessor to NSSGA) conducted a comprehensive study of the factors influencing the performance of dense-graded aggregates base.[10] Talbot's gradation equation with "n" values equal to ⅓ and ½ was utilized to establish target gradations, except for the amount passing the No. 200 sieve.

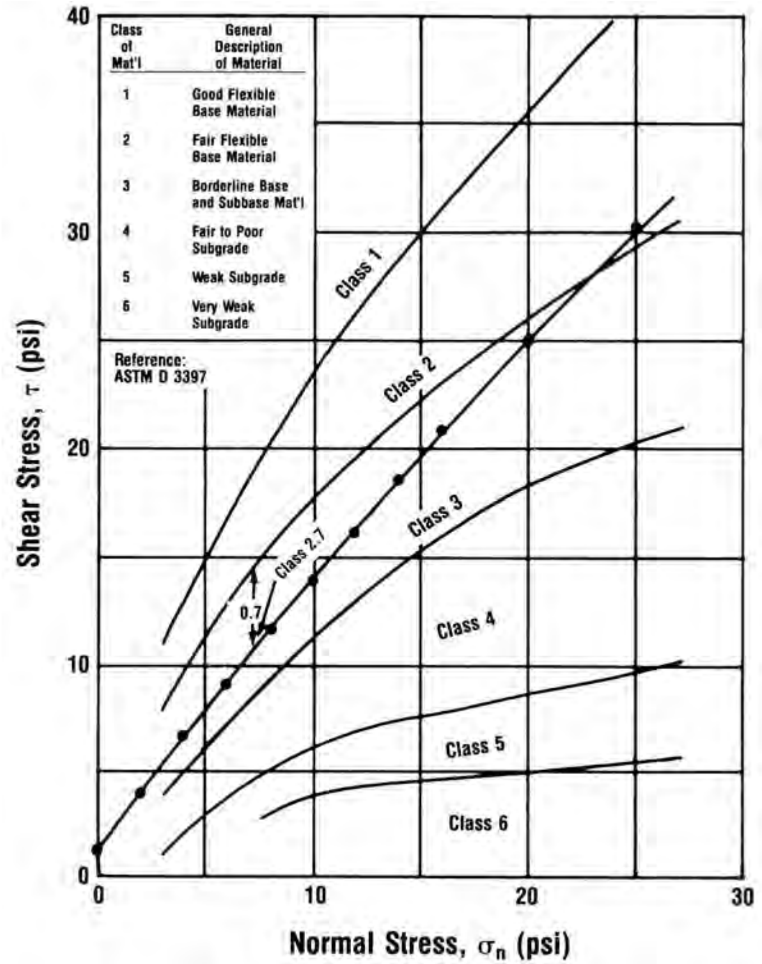


Figure 11.5 Chart for classification of subgrade and flexible-base material using static triaxial test results.

Specimens 6 inches in diameter and 8 inches high were subjected to capillary saturation, and tested utilizing the Texas triaxial procedure. This triaxial test is a static one performed at the strain rate of 1.9 percent per minute and is similar to ASTM Test Method D 3397 (now withdrawn). Several variables were included in the investigation:

1. *Maximum Aggregates Size:* A summary of the gradations and test data included in these tests are presented in Table 11.4. Figures 11.7 and 11.8 show that increased shear strength is achieved with an increase in maximum aggregates size. Figure 11.9 shows for a given stress state and aggregates type, axial strain decreases with increasing aggregates size indicating an increase in stiffness of the specimen.

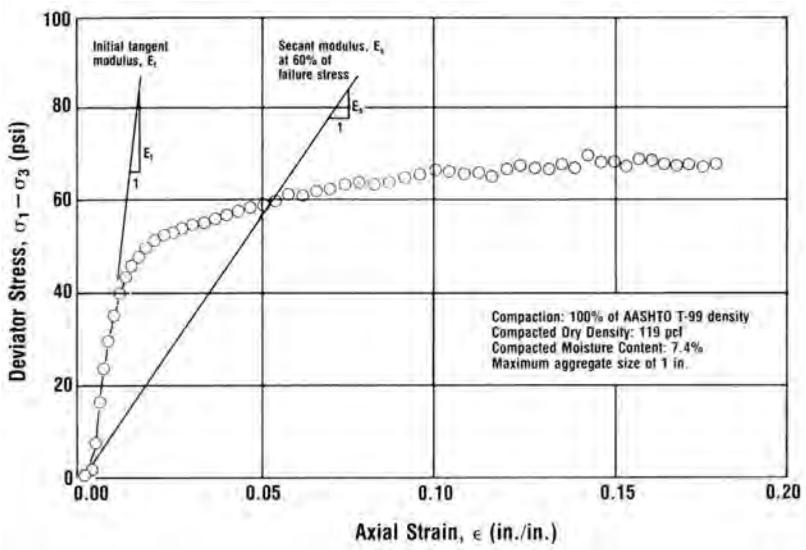


Figure 11.6 Static triaxial test results showing deviator stress plotted against axial strain.

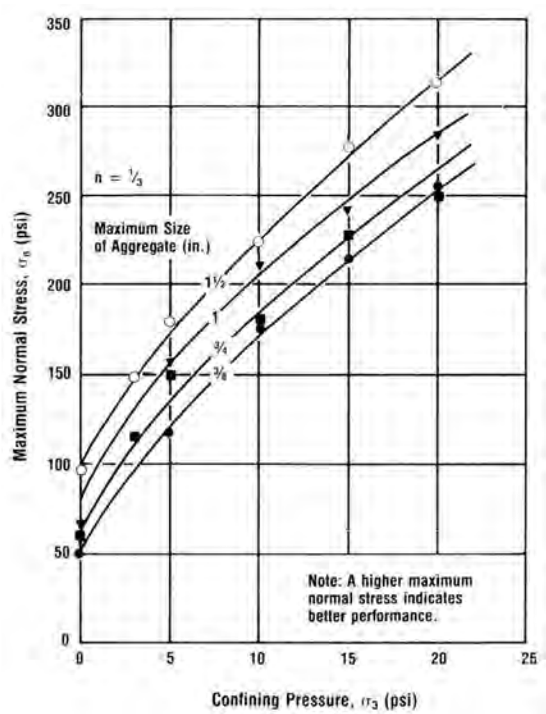


Figure 11.7 Static triaxial test results showing effects of increased shear strength with increased maximum aggregate size: n=⅓.

Table 11.4 Test Results Showing Effect on Maximum Sizeof Aggregate[10]

Identification Maximum Size of Aggregate, in. Talbot n Value[(1)]	3/8 1/3	3/4 1/2	3/4 1/3	1 1/2	1 1/3	1 1/2 1/2	1 1/2 1/3
Properties of Mixes							
Gradation							
Total % passing							
1½ in.						100	100
1 in.				100	100	82	86
¾ in.		100	100	87	90	71	78
½ in.		82	87	71	79	58	69
⅜ in.	100	71	79	61	71	50	62
No. 4	79	50	63	43	57	35	50
No. 8	63	35	49	31	44	25	38
No. 16	50	25	40	22	36	18	31
No. 30	40	18	31	15	28	12	24
No. 40	36	15	28	13	25	11	22
No. 50	33	13	24	11	22	9	20
No. 100	25	9	20	8	18	6	16
No. 200	14[(1)]	6	16	5	14	4	12
Bulk Specific Gravity, Dry	2.69	2.69	2.69	2.69	2.68	2.69	2.68
Dry Weight, lb/cu ft[2]	144.4	140.5	143.0	144.3	145.0	145.0	146.0
Voids after Molding, %	14.0	16.3	14.8	14.0	13.2	13.9	13.0
Molding Moisture, %	6.0	5.2	5.7	5.0	5.2	5.0	4.8
Moisture at Time of Test, %	5.8	4.4	5.1	3.9	4.7	3.5	4.2

Triaxial Compression Test[10]

Lateral Pressure (psi)							
	Maximum Normal Stress (psi)						
0	52	41	62	54	63	52	95
3	—	108	115	123	142	136	147
5	116	142	148	—	156	162	178
10	175	179	178	202	209	215	222
15	213	210	227	—	240	252	276
20	252	252	284	285	282	296	312
25	287	—	—	—	—	—	—
	Normal Stress, psi at 2% Strain						
0	51	(3)	58	(3)	(3)	(3)	(3)
3	—	106	109	120	142	126	146
5	114	140	143	—	154	151	178
10	163	167	160	187	209	193	221
15	186	192	220	—	239	230	275
20	215	235	242	258	275	266	310
25	230	—	—	—	—	—	—
	Static Modulus of Deformation (psi)						
20	12,000	20,000	14,000	20,000	20,000	22,000	23,000

Note: 1. A lesser amount of fines than the theoretical gradings
2. Determined immediately after molding
3. Maximum stress occurred at a lesser strain

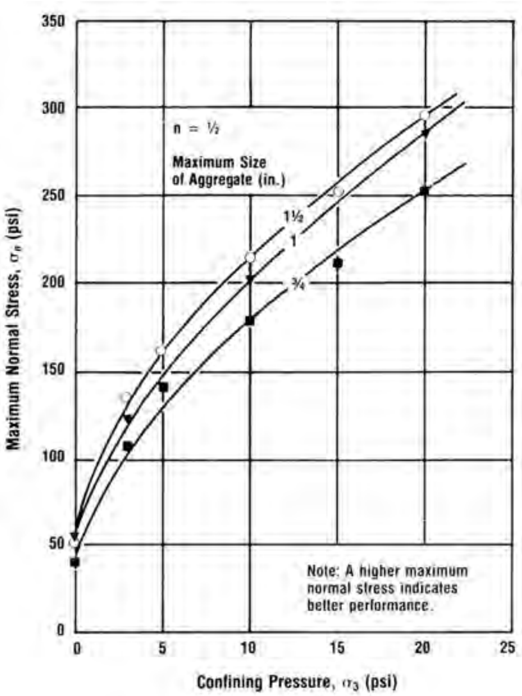


Figure 11.8 Static triaxial test results showing effects of increased shear strength with increased maximum aggregate size: n=½.

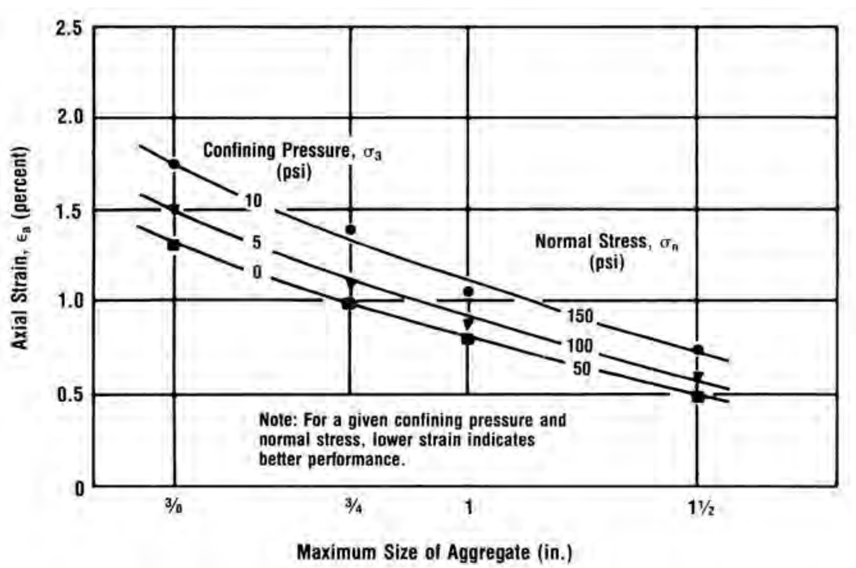


Figure 11.9 Example showing axial strain decreasing with increasing aggregate size—static triaxial test results.

2. *Fines Content:* Fines are usually defined as the amount of material passing the No. 200 sieve. Dense graded crushed stone gradations were evaluated having a ¾ inch maximum size aggregates and containing 1 to 10 percent fines. The results, summarized in Figures 11.10 and 11.11, show that as fines are initially added, voids in the spaces between the coarse aggregates particles are filled and shear strength increases. With the addition of more fines, the coarse aggregates particles are pushed apart. In this state, the coarse aggregates float in a matrix of fine material, which has a lower shear strength resulting in a decrease in shear strength of the mixture. This decrease in shear strength occurs when the amount of fines added becomes greater than that required to achieve maximum density.

   The optimum amount of fines for developing maximum shear strength is related to the maximum size of aggregates in a well-graded mixture. As the maximum aggregates size increases, the optimum fines content decreases because fewer void spaces exist that require filling with fines before coarse aggregates separation occurs. For mixtures graded approximately according to the Talbot equation with an n value equal to ⅓, the optimum fines content varies from about 9 percent for a maximum aggregates size of ¾ inch to only 6 percent for a maximum aggregates size of two inches. Frequently a fines content lower than the optimum required for developing maximum shear strength is used to reduce the potential of frost susceptibility and increase the rate at which water flows from the aggregates.

3. *Plasticity:* The important detrimental effects of increased plasticity index (PI) are shown in Figures 11.12 and 11.13. The maximum aggregates size was varied from ⅜ to 1½ inches.

4. *Particle Shape:* Gravel and crushed gravel size fractions were prepared from the same material source and blended as shown in Table 11.5. The fines fraction in all of the blends was 8 percent silty clay. All mixes were non-plastic. Figures 11.14 and 11.15 show that shear strength increases with an increasing percentage of crushed particles. The beneficial effects of crushing the material smaller than the No. 4 sieve fraction are illustrated in Figure 11.15. This figure compares Mixes A, F and G, which contain varying degrees of crushed fines, with Mix E which has all natural fines.

5. *Aggregates Type:* Six mixtures, described in Table 11.6, were tested. They were composed of various blends of plus No. 4 sieve size material, minus No. 4 to plus No. 200 material, and fines (minus No. 200 material). Shear strengths for the various blends are presented in Figure 11.16 and strain data are shown in Figure 11.17. The 100 percent crushed stone mixture (Mix O) provided the largest shear strength and the Bank Run Gravel (Mix S) the lowest, with the blends having shear strengths falling in between. The addition of both crushed aggregates smaller than the No. 4 sieve and limestone fines was beneficial.

   Specimens containing blends of the crushed material had the greatest stiffness (which is beneficial to good performance), as indicated in Figure 11.17 by a decrease in strain. The gravels (Mixes N and S) had the lowest stiffness.

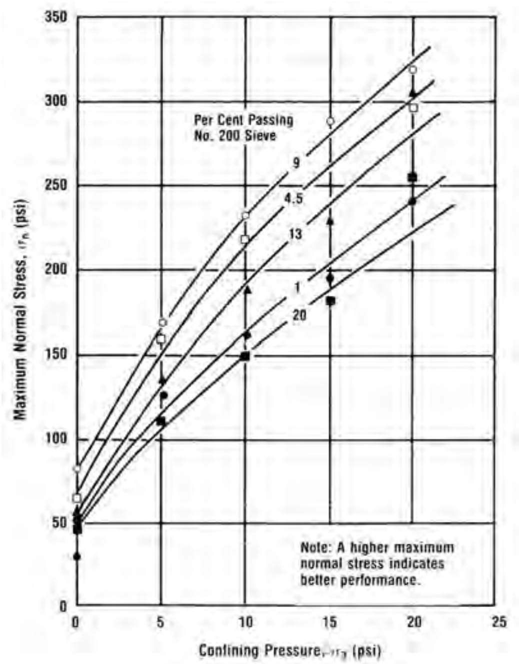


Figure 11.10 Example showing optimum fines content – static triaxial test results.

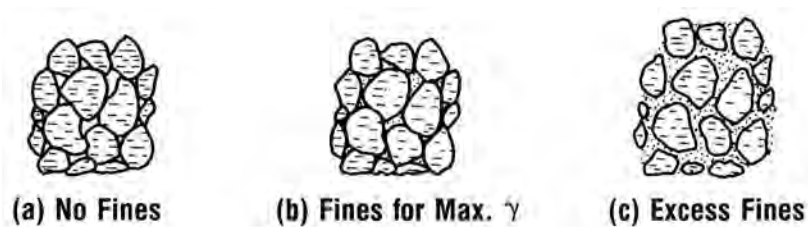


Figure 11.11 Influence of fines content on maximum density of granular materials.[14]

6. *Density:* An increase in density increases the shear strength of aggregates. Figure 11.18 illustrates the important beneficial effect of increased density for a well-graded crushed stone when the density is increased from 100 percent of AASHTO T-99 maximum dry density (138 pcf) to 100 percent AASHTO T-180 maximum dry density (145.8 pcf). Figure 11.19 illustrates a reduced, but positive, effect of increasing density for a well-graded gravel compacted 1.3 percent wet of AASHTO T-99 optimum moisture content. Increasing the density has a significant beneficial effect for an open graded AREA No. 4 ballast, as illustrated in Figure 11.20. This ballast has extensive coarse aggregates to coarse aggregates particle contact, which is an important factor for high shear strength.

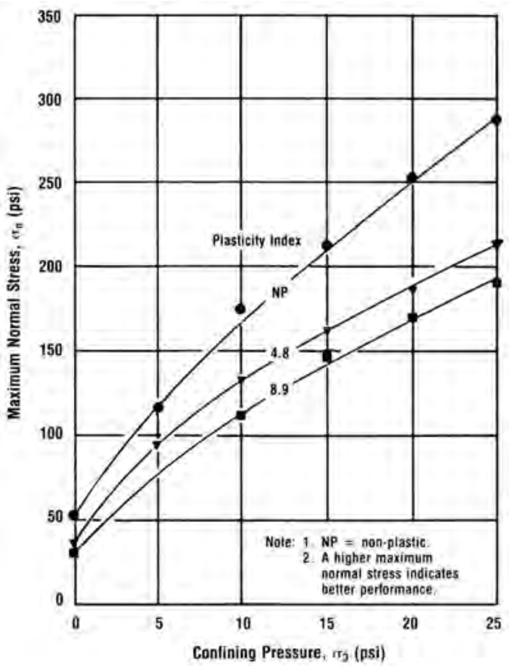


Figure 11.12 Effect of plasticity index on shear strength for ⅜ in. maximum size aggregate.

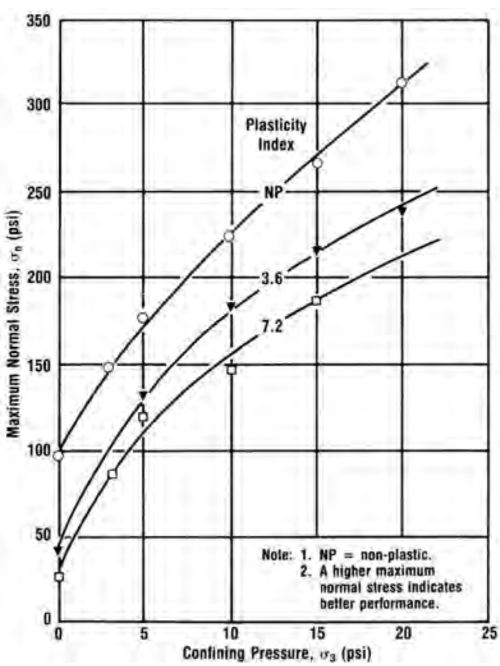


Figure 11.13 Effect of plasticity index on shear strength for 1 ½ in. maximum size aggregate.

Table 11.5 Summary of Test Results for Gravel an Crushed Gravel Mixes A Through G[10]

Mix No.	A	B	C	D	E	F	G
			Properties of Mixes				
Composition[(1)]							
Coarse Aggregate							
Gravel, %	—	25	50	75	100	—	100
Crushed Gravel, %	100	75	50	25	—	100	—
Fine Aggregate							
Natural Sand, %	80	85	90	95	100	—	—
Gravel Screenings, %	20	15	10	5	—	100	100
Material Passing							
No. 200 Silty Clay, %	100	100	100	100	100	100	100
Bulk Specific Gravity, Dry	2.60	2.60	2.59	2.58	2.58	2.60	2.58
Dry Unit Weight, lb/cu ft[(2)]	138.8	138.5	139.0	139.3	140.2	134.4	134.8
Voids after Molding, %	14.5	14.4	14.0	13.6	12.9	17.2	16.2
Molding Moisture, %	6.2	6.0	5.8	5.7	5.7	6.1	5.9
Moisture at Time of Test, %	6.0	5.8	5.7	5.6	5.7	5.6	5.6
			Triaxial Compression Test				
Lateral Pressure (psi)			**Maximum Normal Stress (psi)**				
0	15	17	16	15	14	16	16
5	72	64	64	50	56	74	77
10	107	104	102	89	95	115	117
15	154	137	131	122	125	172	164
20	189	170	161	150	156	190	208
			Normal Stress, psi at 2% Strain				
0	(3)	(3)	(3)	(3)	(3)	(3)	(3)
5	(3)	64	64	52	55	(3)	(3)
10	100	100	101	85	92	114	116
15	136	133	126	114	121	171	164
20	173	159	154	130	146	190	198
			Modulus of Deformation (psi)				
20	12,000	11,000	11,000	8,000	10,000	13,000	14,000

Note: 1. Grading of these mixes were prepared according to Talbot's equation $P = (d/D)^n$ with maximum size of aggregate = 1 in. and value of $n = 1/3$. Modification was made only on material passing No. 200 sieve to be 8%.
2. Determined immediately after molding
3. Maximum stress occurred at a lesser strain

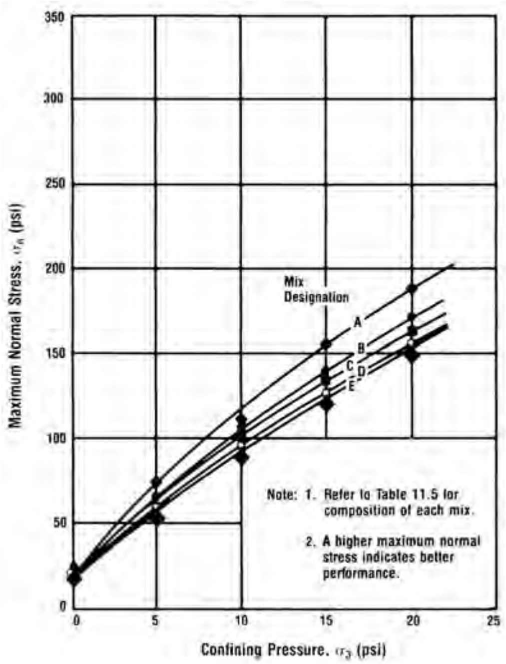


Figure 11.14 influence of type aggregate mix (gravel, crushed gravel and their blends) on performance.

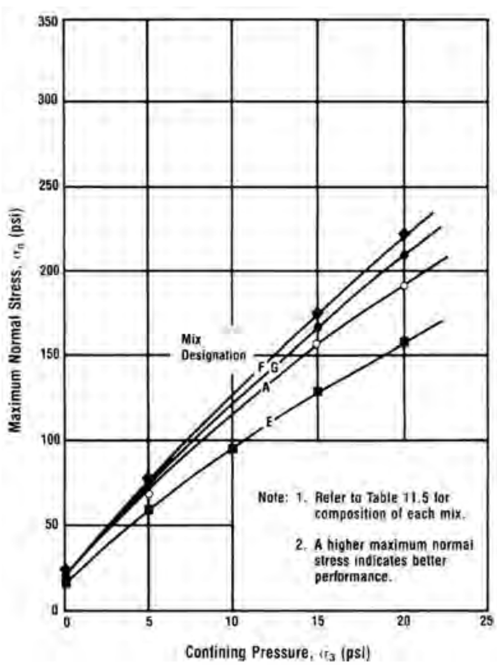


Figure 11.15 Relationship of principal stresses for crushed fines and natural lines.

Table 11.6 Summary of Test Results for Mixes O Through S[10]

Mix No.	O	R	L	T	N	S
Properties of Mixes						
Composition						
Coarse Aggregate						
Limestone, %	100	50	100	50	—	—
Gravel, %	—	50	—	50	100	100(1)
Fine Aggregate						
Limestone, %	100	50	100	50	—	—
Natural Sand, %	—	50	—	50	100	(1)
Material Passing No. 200						
Limestone, %	100	100	—	—	—	—
Silty Clay, %	—	—	100	100	100	(1)
Gradation						
Total % Passing						
1½ in.						100
1 in.	100	100	100	100	100	86
¾ in.	90	90	90	90	90	76
½ in.	79	79	79	79	79	62
⅜ in.	71	71	71	71	71	55
No. 4	57	57	57	57	57	45
No. 10	42	42	42	42	42	38
No. 40	25	25	25	25	25	21
No. 200	14	8	8	8	8	5
Liquid Limit(2)	NP	NP	NP	NP	17.1	NP
Plasticity Index(2)	NP	NP	NP	NP	2.6	NP
Bulk Specific Gravity, Dry	2.68	2.64	2.69	2.63	2.58	2.55
Dry Unit Weight, lb/cu ft^3	145.0	138.4	142.3	140.9	141.0	137.0
Voids after Molding, %(3)	13.2	15.9	15.3	14.3	12.5	13.9
Molding Moisture, %	5.2	5.3	5.3	5.5	5.5	6.5
Moisture at Time of Test, %	4.7	5.3	4.8	5.1	4.9	5.8
Triaxial Compression Test						
Lateral Pressure (psi)	**Maximum Normal Stress (psi)**					
0	63	17	46	22	16	9
5	156	101	119	72	64	52
10	209	147	140	108	106	97
15	240	182	166	150	132	139
20	282	217	220	186	160	160
	Normal Stress, psi at 2% Strain					
0	(4)	(4)	(4)	(4)	(4)	(4)
5	154	101	118	72	64	52
10	209	146	134	107	100	95
15	239	181	152	144	125	136
20	275	217	187	176	155	144
	Modulus of Deformation (psi)					
20	20,000	20,000	—	16,000	12,000	10,000

Notes: 1. Bank Run Gravel
2. NP = Non-Plastic
3. Determined immediately after molding
4. Maximum stress occurred at a lesser strain

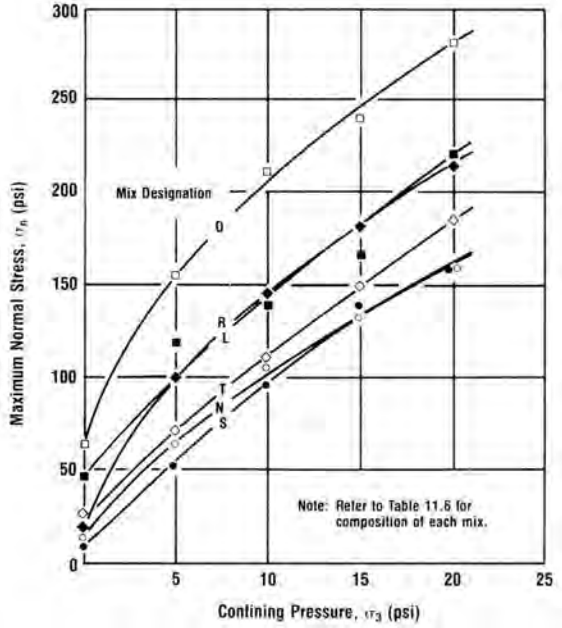


Figure 11.16 Relationship of principal stresses for limestone, gravel, and limestone-gravel blends.

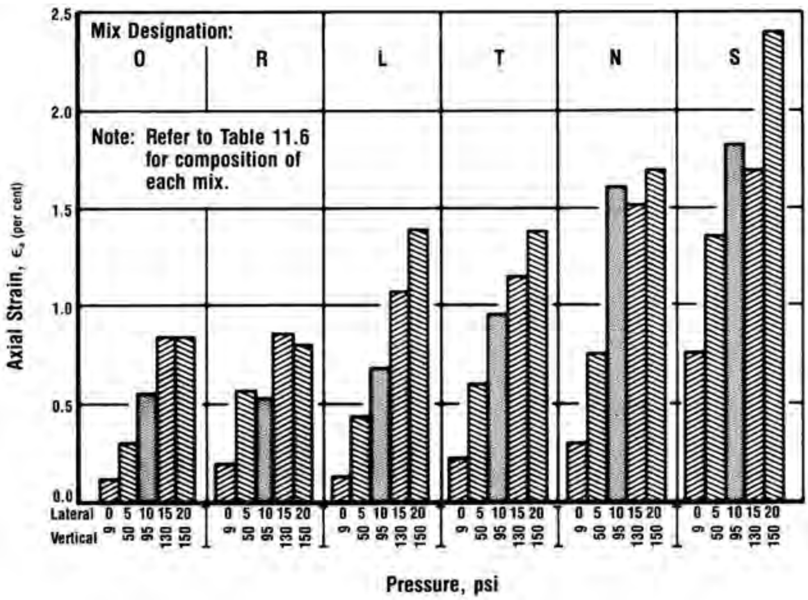


Figure 11.17 Strain at constant confining pressure for limestones, gravel and limestone-gravel blends.

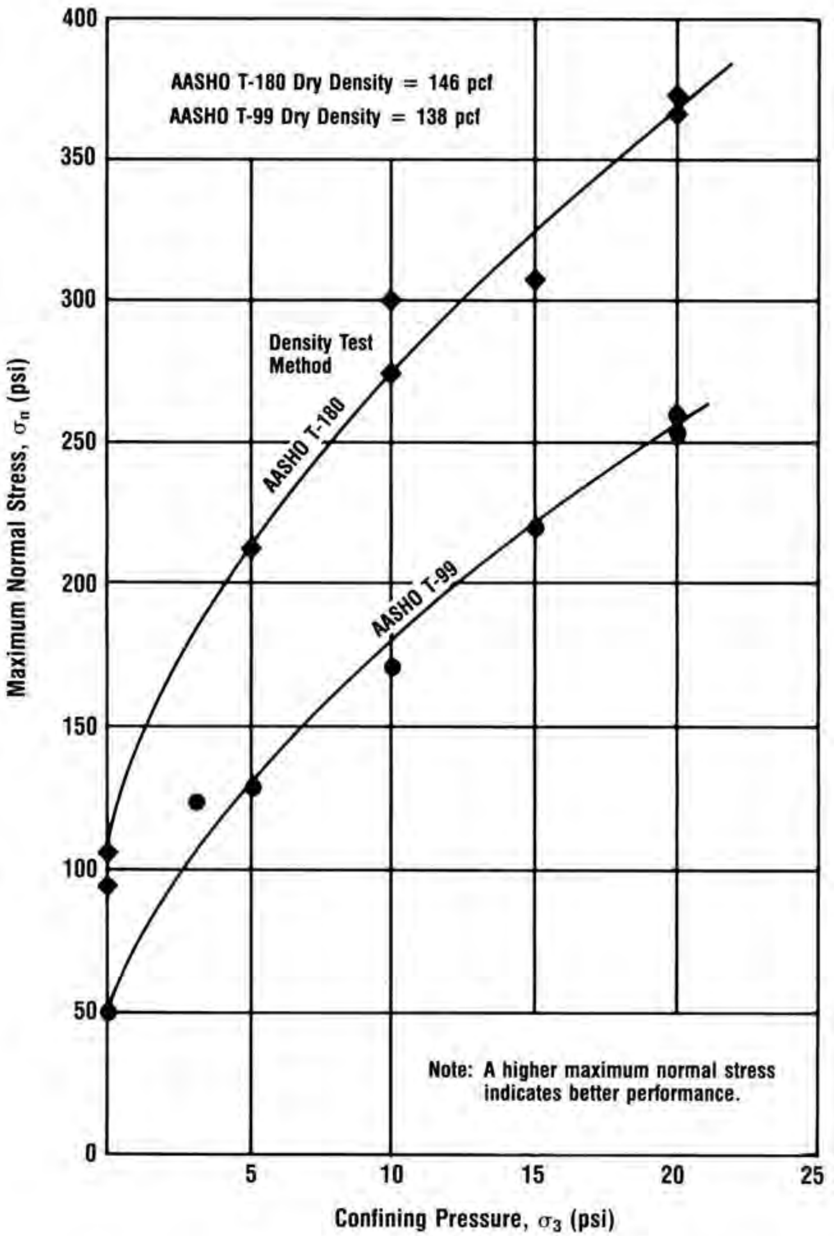


Figure 11.18 Relationship of principal stresses for different densities.

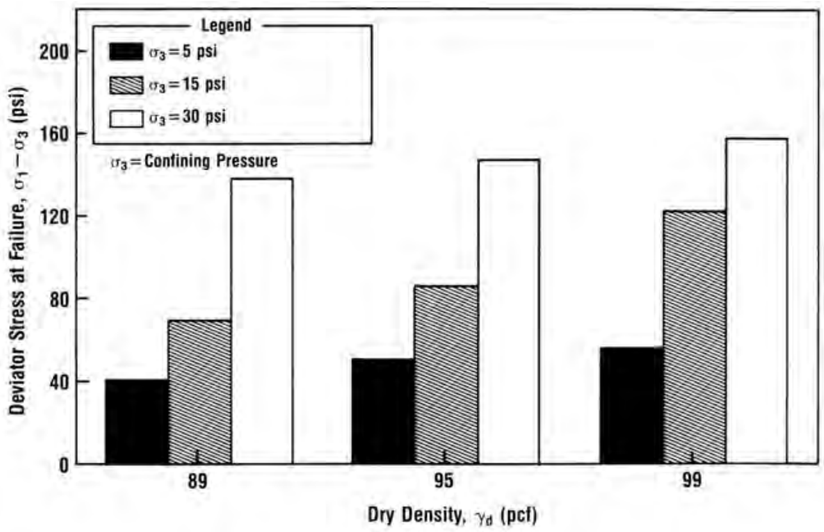


Figure 11.19 A well-graded gravel compacted at 1.3% wet of optimum of AASHTO T-99.

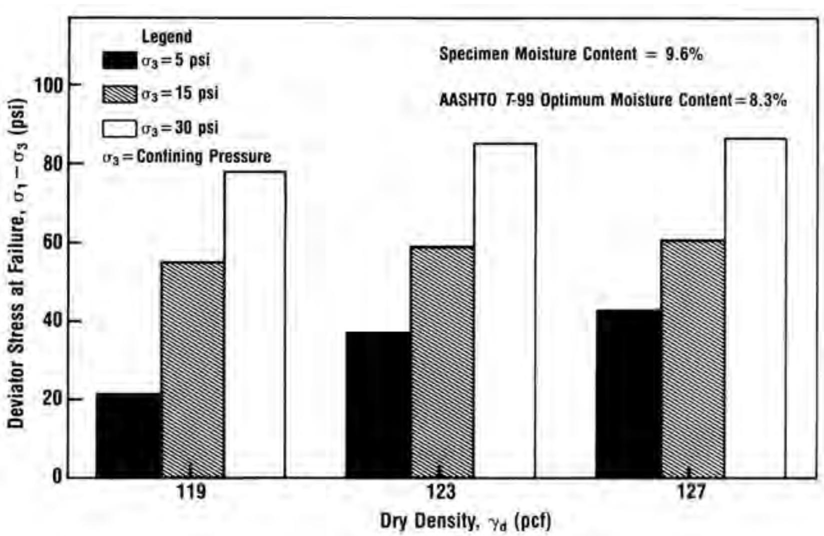


Figure 11.20 AREA No. 4 ballast compacted at AASHTO T-99 optimum moisture.

California Bearing Ratio

CBR Test: The *California Bearing Ratio* (CBR) test (AASHTO Test Method T-193; ASTM Test Method ASTM D 1883) is an empirical test method. In this test, the aggregates are compacted into a 6-inch diameter mold to form a specimen 4.6 inches high. The maximum particle size permitted is ¾ inch. Specimen conditioning usually consists of a 96-hour soaking period to simulate wet pavement conditions. Soaking is particularly important if a significant quantity of minus No. 200 material is present. The specimen is then penetrated at a loading rate of 0.05 inches per minute with a piston having an end area of 3 inches.[2] The specimen remains in the mold throughout the testing process. The CBR is calculated by dividing the piston pressure at 0.1 or 0.2 inch penetration by standard reference values of 1,000 psi for 0.1 inch penetration and 1,500 psi for 0.2 inch These standard values represent the pressures observed for a high quality, well-graded crushed stone reference material. The calculated ratio of pressures at the appropriate penetrations is multiplied by 100 to give the CBR value expressed as a percent.

Factors Influencing CBR Value: CBR values are influenced by the same factors previously discussed for triaxial testing and the general trends are similar. Factors contributing to developing high CBR values are: (1) a large maximum size, (2) a proper gradation defined by good representation of various grain size fractions, (3) a greater amount of crushed material and improved geometric properties (shape/angularity/ surface texture), and (4) a reduced plasticity index (PI). For a given granular material, the CBR value can be significantly increased by increasing the compacted density, as illustrated in Figure 11.21 for three dense graded stone base materials.
High quality, dense graded crushed stone commonly has CBR values in excess of 100. Well graded gravel (AASHTO classification A-1-a; Unified classification GW) typically have CBR values ranging from 30 to 80. Less well graded gravel (AASHTO classes A-1-b, A-3-4, A-2-5; Unified classes GP, GM, GC) typically develop lower CBR values ranging from about 20 to 60. The CBRs for natural sand generally vary from 10 to 30. When interpreting CBR data for aggregates, it is emphasized that the performance of aggregates as a structural layer is not directly proportional to its CBR value. For example, aggregates having a CBR value of 150 percent are not twice as good as one having a CBR of 75 percent.

Many base course aggregates specifications require CBRs in excess of 80 which, for example, is recommended by The Asphalt Institute.[11] NSSGA[12] recommends a minimum CBR value of 100, and the Department of Defense flexible pavement design procedure[13] assigns a design CBR value of 100 to graded crushed aggregates. Most aggregates subbase specifications require minimum CBR values in the range of 20 to 50 percent. The Asphalt Institute[11] requires 20 percent, which for most applications is too low.

Hveem Stabilometer (Resistance R-Value)

The Hveem Stabilometer test (AASHTO T-190; ASTM D-2844) was developed by the California Highway Department and is used by several other western state transportation agencies. The Hveem Stabilometer test is not as widely accepted and utilized as the CBR test.

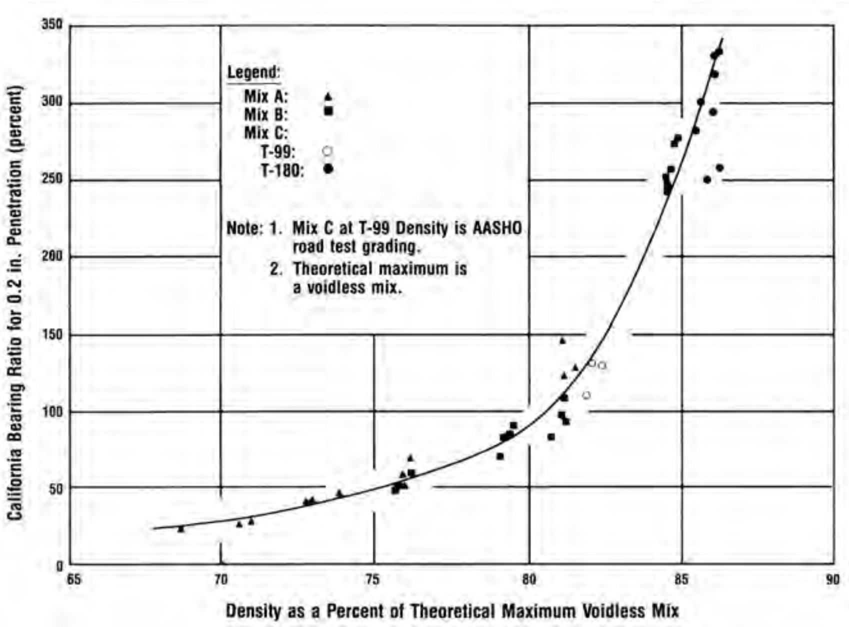


Figure 11.21 Relationship between CBR and compactive effort (expressed as a percent of a voidless mix).

The compacted stabilometer test specimen is 4 inches in diameter and approximately 2.5 inches high. The procedure is used with maximum particle sizes up to one inch. Yoder and Witczak[14] indicate:

> "The test procedure is adapted so that resistance to deformation is expressed as a function of the ratio of the transmitted lateral pressure to that of the applied vertical pressure. A vertical pressure of 160 psi is used."

The resistance value (R) is calculated from the stabilometer test data. Resistance R-values vary from 0 for water to approximately 100 for a stiff, nearly rigid material. Typical R values for aggregates vary from the 80s and 90s for dense graded, high density crushed stone base course down to the 50s and 60s for less well-graded and higher fines content gravelly materials.

Strength Correlations

Static triaxial tests, CBR tests, and Hveem Stabilometer tests are utilized by various agencies. The general correlation shown in Figure 11.22 between these strength values and selected soil classification systems is quite useful. Considerable judgment, however, must be used when such correlations are employed for design. Preferably, laboratory tests should be performed on each material such as the repeated load triaxial test, which is described subsequently in this chapter, or the CBR test.

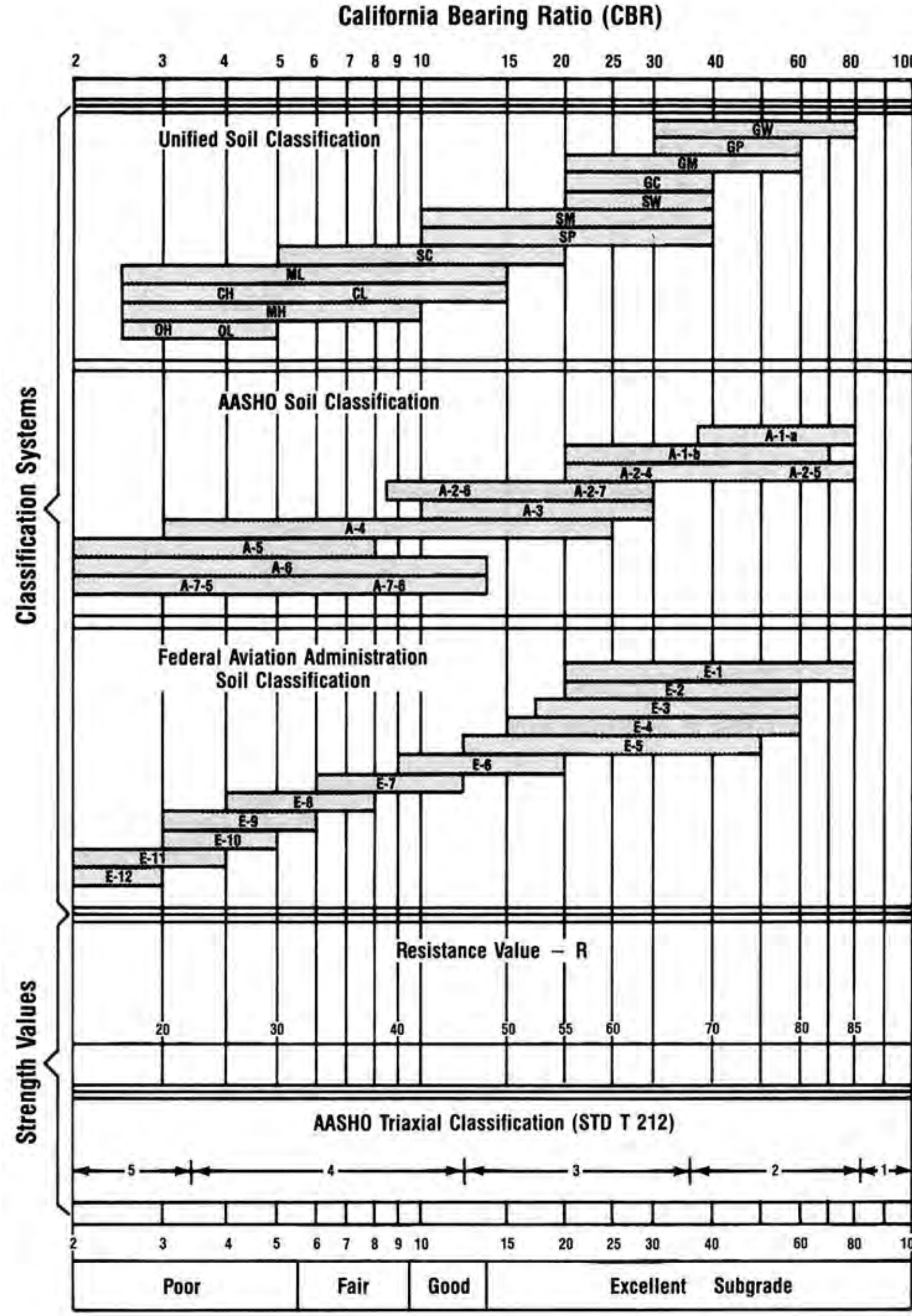


Figure 11.22 Correlstion of strength values and classification systems to CBR value.

Aggregates Geometric Characteristics and Effects

Particle Index: Huang[15-17] has suggested that pertinent coarse aggregates particle geometric characteristics are shape, angularity and surface texture. The particle index testing concept developed by Huang "*provides a quantitative evaluation of geometric characteristics*." The basic concept of the particle index test is:[14]

> "Void characteristics in a uniform-sized coarse aggregates when compacted in a standard mold indicate the combined features of shape-angularity-surface texture."

Test results are expressed as the particle index (Ia) of the aggregates. A mass of single-sized, highly polished aluminum spheres has a particle index of 0. Typical particle index values vary from about 4 for rounded gravel with smooth surfaces to about 20 for crushed stone with angular edges and a rough surface texture.

ASTM D 3398 presents the details of the particle index test procedure and is based on Huang's original concepts. The significance and use of the particle index test, as given in ASTM Test Method D 3398, is as follows:

> "The method provides an index value to the relative particle shape and texture characteristics of aggregates. this value is a quantitative measure of aggregates shape and texture characteristics that may affect the performance of road and paving mixtures. The method has been used to indicate the effects of these characteristics on the compaction and strength characteristics of soil-aggregates and asphalt concrete mixtures."

The particle index test can be used to characterize sieve fractions ranging from minus ¾ inch to the plus No. 200 sieve size. This test, as specified by ASTM Test Method D 3398, requires using a 6-inch diameter steel mold that takes about 11 pounds of material to fill. McLead and Davidson[18] found that a smaller mold can be successfully used to obtain a reliable particle index. Pouring tests also have been used to evaluate overall aggregates index properties.[19,20]

Particle Index Test Results: Figure 11.23 shows the relationship between the particle index and the compaction characteristics of dense graded aggregates mixtures as indicated by the voids in the aggregates when compacted to ASTM D 698 maximum dry density. All mixtures had a maximum aggregates size of 3.4 inches.

Different gradations, however, were used having values of the exponent in Talbot's equation (11-1) of n = 0.40, 0.45 and 0.50. The data are presented in terms of the ratio of volume of solids to the volume of voids (1/void ratio) to eliminate the effects of variable aggregates specific gravities. The particle index effect is most pronounced (as indicated by the steeper slope in Figure 11.23) for larger values of Talbot's gradation (n values) that provide a greater concentration of coarse aggregates in the mixture. The compactability of aggregates is inversely related to shear strength. Aggregates mixtures having higher shear strengths more effectively resist shear stresses induced by the compaction effort. Thus, for a given compactive effort, these mixtures achieve lower maximum dry densities.

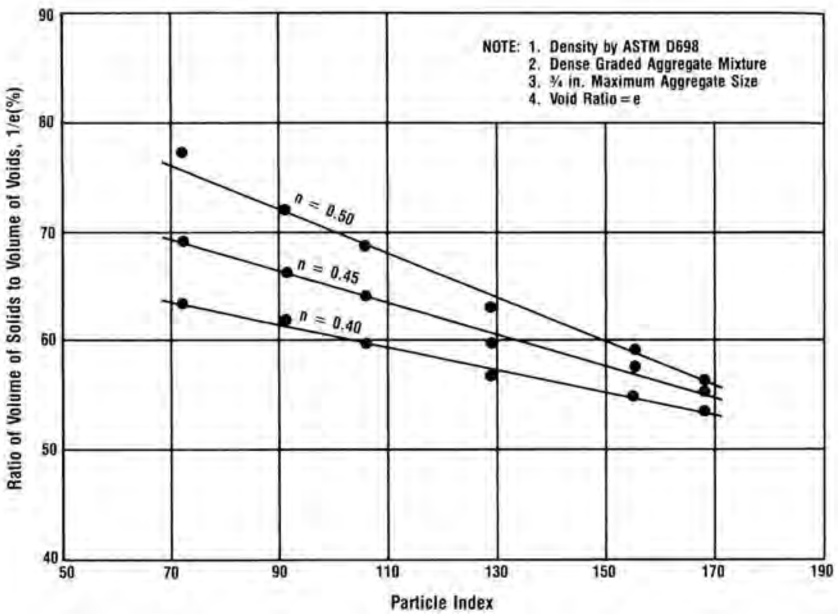


Figure 11.23 Effect of gradation expressed as Talbot's "n" value on voids in compacted aggregate.

The effect of the particle index on shear strength is shown in Figure 11.24. The data are for mixtures with a maximum aggregates size of ¾ inch and are graded according to Talbot's equation with an "n" value of 0.4. The minus No. 4 sieve fraction in all of the mixtures was the same. The triaxial specimens were compacted to 100 percent of ASTM D 698 maximum dry density at optimum moisture content and tested in a drained condition. The shear strength, as indicated by a larger maximum deviator stress, increased with the increasing particle index value. The effect of geometric characteristics, as indicated by the particle index, is greater at the higher confining pressure. The angle of internal friction (ϕ) also increases with increasing particle index, as shown in Figure 11.25. The value of the angle of internal friction becomes greater as the gradation becomes coarser as determined using a greater Talbot "n" value in equation 11-1. These results clearly show that aggregates geometric characteristics are important factors that influence compaction and shear strength properties.

Aggregates Influence Factor: An Aggregates Influence Factor (AIF)[21,22] has been used to show the effects of geometric properties on the resilient and rutting behavior of five different types of aggregates. The AIF is calculated based on the values of sphericity, roundness, angularity and surface texture. Larger AIF values indicate particles that are less spherical, less rounded, more angular and have a rougher surface texture. Larger AIF values appear to be associated with increased resilient moduli and better resistance to rutting, as illustrated in Figure 11.26.

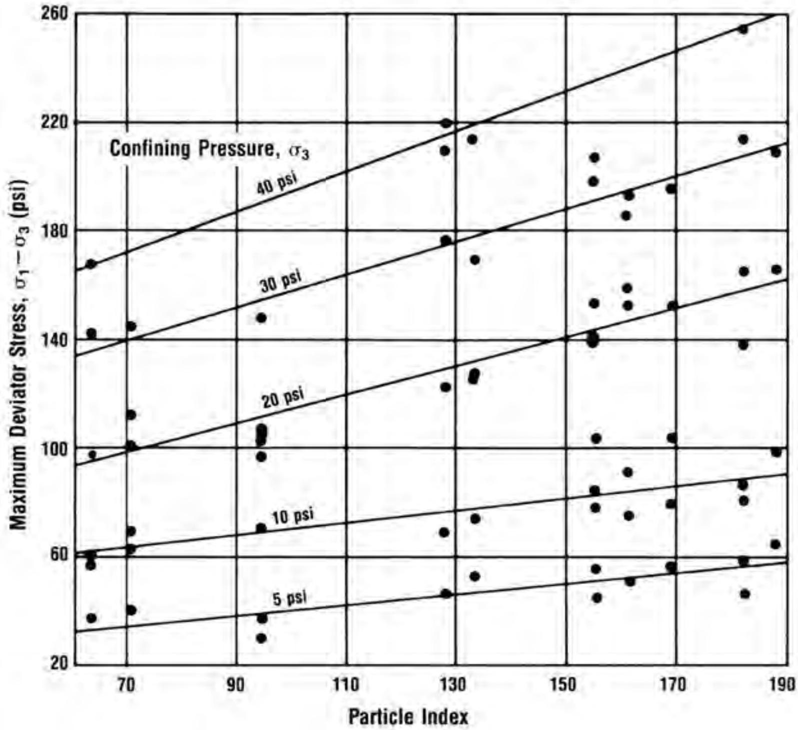


Figure 11.24 Effect of particle shape on shear strength.

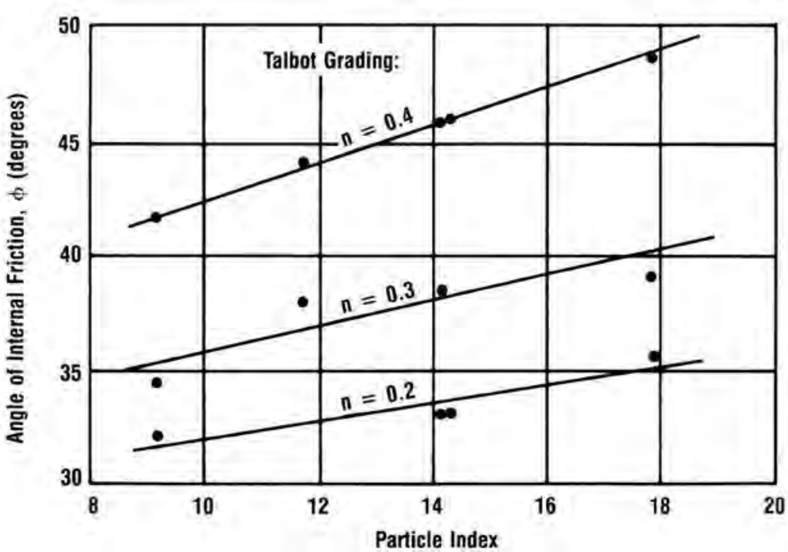


Figure 11.25 Effect of particle shape on angle of internal friction.

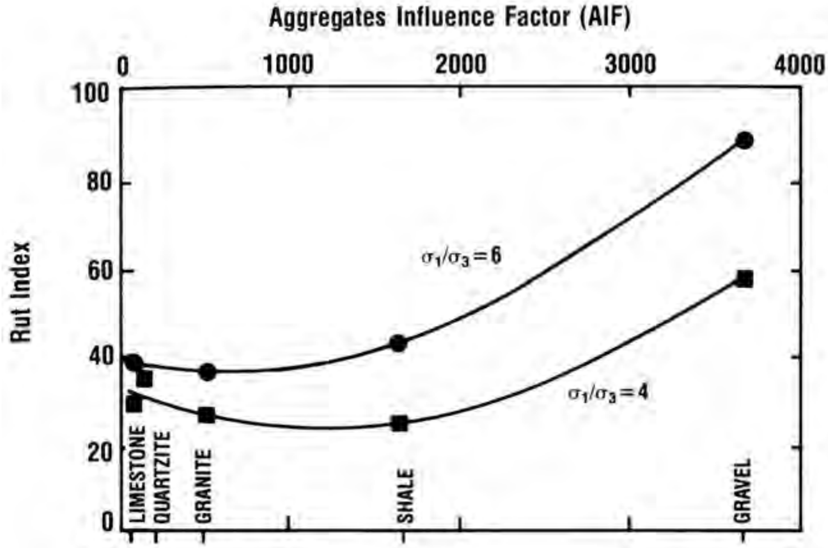


Figure 11.26 Effects of aggregates geometric properties on rutting.

Importance of Smaller Size Crushed Stone: Geometric aggregates properties are important for both the plus No. 4 sieve size particles and smaller size fractions in an aggregates. The importance of the minus No. 4 sieve size fraction has been clearly demonstrated by a comprehensive study[23] of the field shear strength of soil-aggregates mixtures performed at 147 test sites. Mixtures having crushed stone smaller in size than the No. 4 sieve provided better field stability than soil as measured by the Burgraff shear test[71] Increased resilient moduli and rutting resistance also have been observed when crushed limestone dust (minus No. 100 sieve size) was substituted for soil fines[24]

Current practices generally consider aggregates geometric properties only in a subjective and/or semi-quantitative manner. Typically, specifications are based on a visual determination of the percentage of crushed particles. A *crushed particle* is generally defined as a particle with at least two fractured faces, but some specifications require only one fractured face.

Repeated Load Triaxial Testing

Introduction: Repeated load triaxial testing provides important material response data for the analysis and design of pavements and track structures containing aggregates layers. Static testing procedures in general are not adequate for characterizing the behavior of soil and aggregates materials subjected to the impulse type repeated loading representative of moving wheel loads. A cylindrical specimen of material is used in the repeated load test. A constant all-around confining pressure (s_3) is applied to the specimen. Then the specimen is subjected to a repeated deviator stress (σ_1 - σ_3) to simulate a moving wheel load (refer to Figure 11.27a).

Repeated load triaxial testing is used to quantify resilient moduli and permanent deformation behavior. In simple terms, the *resilient modulus* is defined as the maximum deviator stress applied to the cylindrical specimen of material divided by the maximum recoverable axial strain. In recent years, repeated load triaxial testing has received considerable emphasis in the evaluation of aggregates bases, subgrade soils and asphalt concrete. In a well-designed pavement or track structure, the permanent strain accumulated per load cycle is small compared to the total strain. When subjected to a large number of load repetitions, however, permanent strain, which is closely related to rutting, can become relatively large.

The 1986 AASHTO guide[25] uses resilient moduli to characterize subgrade soils and assign *layer coefficients* to aggregates base and subbase layers. AASHTO defines the layer coefficient as:

> "The empirical relationship between structural number (SN) and layer thickness which expresses the relative ability of a material to function as a structural component of the pavement."

However, state transportation agencies are experiencing considerable difficulty in establishing appropriate resilient moduli values to use in the AASHTO guide. Suggested procedures for repeated load testing have been proposed by several agencies and groups[26,27,28] AASHTO Test Method T-274-82 is available for determining the resilient modulus of subgrade soils. Because of widespread dissatisfaction with this procedure, AASHTO has withdrawn this test method and is developing a new one applicable to both subgrade and aggregates bases. ASTM is currently developing a suggested procedure.

A constant confining pressure σ_3 is used for routine testing of aggregates. Both pneumatic and electrohydraulic repeated loading equipment have been successfully utilized. The equipment must be capable of producing a load pulse duration of approximately 25 to 150 msec. The load pulse is generally repeated 15 to 60 times per minute.

Axial deformation over a portion, or in some cases the entire length, of the specimen is measured using two linear variable differential transformers (LVDTs) positioned on each side of the specimen. Total, resilient (rebound) and permanent deformations are typically recorded. Figure 11.27b illustrates the resilient and permanent deformation response of an aggregates base or other material when subjected to a repeated load pulse. Repeated load triaxial testing is required to characterize the resilient behavior of granular materials.

Resilient Behavior: A commonly used measure of resilient response is the *resilient modulus* as defined below and shown in Figure 11.27:

$$M_R = \sigma_D/\varepsilon_R \tag{11-9}$$

where

M_R = Resilient modulus (psi)
σ_D = Maximum repeated deviator stress, $\sigma_1 - \sigma 3$ (psi)
ε_R = Recoverable (resilient) axial strain (in./in.)

The resilient response of aggregate, such as aggregate base, is highly stress dependent. Aggregate materials stiffen (i.e., undergo an increase in resilient modulus) with an increase in the confining pressure and to a lesser degree with increasing deviator stress. The *Sigma 3 Model* initially was used to characterize this stress hardening effect. In this type of model, the resilient modulus is related to the confining pressure (σ_3) by the relation:

$$M_R = k_1 \sigma_3^{k_2} \tag{11-10}$$

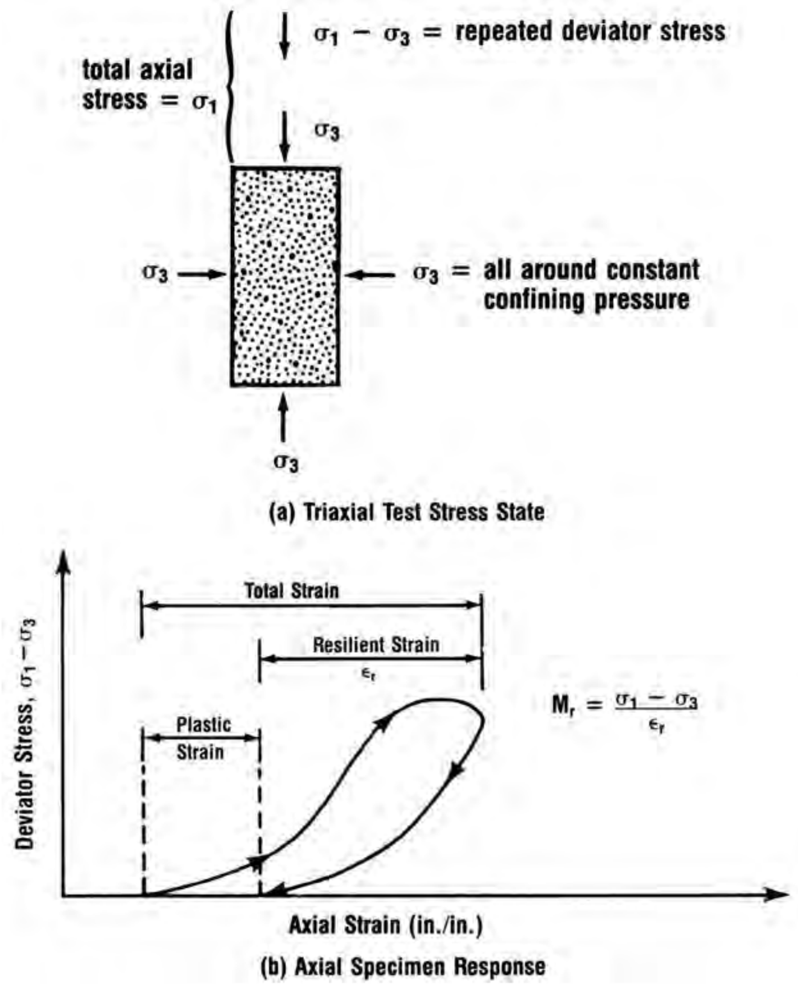


Figure 11.27 Resilient modulus test relationships.

Figure 11.28 shows typical data for a crushed dolomite aggregates. Note the important increase in M_R with increasing confining pressure.

The *Theta Model* provides an improved characterization over the Sigma 3 Model of the stress dependent behavior of granular materials, as illustrated in Figure 11.29. Figure 11.29 is the data from Figure 11.28 re-plotted in terms of Θ, which is the bulk stress applied to the specimen. The Theta Model is presently more frequently used than the Sigma 3 Model and can be expressed as:

$$M_R = k_1 \Theta^{k_2} \tag{11-11}$$

where

M_R = Resilient modulus
k_1 and k_2 = Experimentally derived factors
Θ = Bulk stress $(\sigma_1 + \sigma_2 + \sigma_3)$;

In the triaxial test, the bulk stress $\Theta = \sigma_1 + 2\sigma_3$.

Factors Affecting Resilient Modulus: The generalized influence of selected factors on the resilient modulus of aggregates are as follows:[30-37]

1. *Number of Repetitions:* The resilient response after a limited number of load repetitions (100 or so) is representative of the early behavior of the material. By about 5,000 repetitions, the resilient modulus has started to increase due to densification and reduction in water content caused by drying.

2. *Specimen Utilization:* The same specimen is usually used to measure the resilient response over a wide range of stress levels. The stresses can be applied in any order if the repeated stress states are not greater than approximately 60 percent of the ultimate shear strength of the material.

3. *Stress Pulse Duration:* The resilient modulus of aggregates base is only minimally affected by variations in stress pulse duration. In fact, Kalcheff and Hicks[38] demonstrated that if the stress pulse is rapidly applied and then sustained, the resilient response is the same as that obtained from a rapidly applied and released short duration stress pulse of the same magnitude. Barksdale and Itani[21] have found that a slow cyclic test:

   > "Can be used to evaluate the resilient modulus of unbound aggregates bases for design purposes. The modulus obtained from a slow cyclic test could, if desired, be increased by 10 percent to give better results, which is in agreement with other studies."

   A strain rate of 0.25 percent per minute and five cycles of loading were used in their static tests.

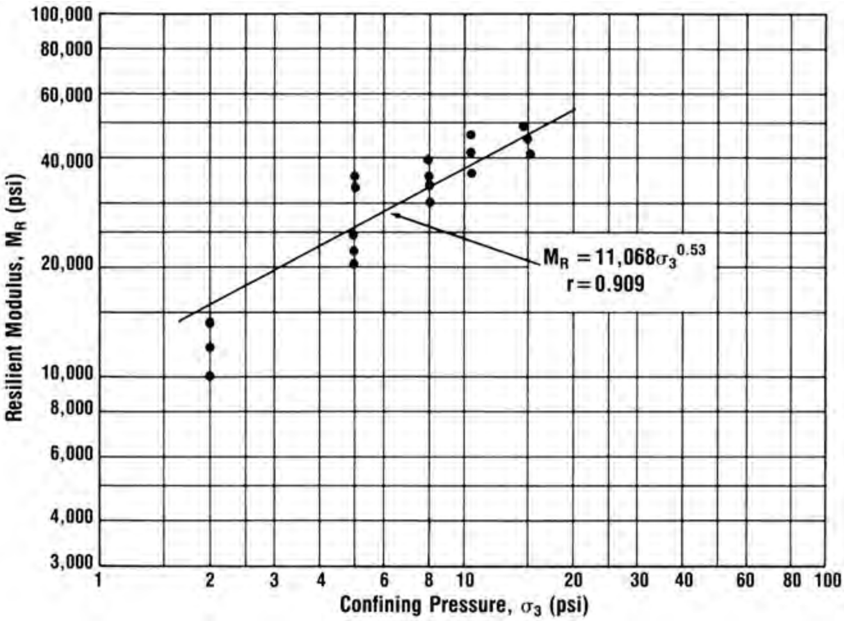


Figure 11.28 Relationship between resilient modulus and confining pressure for a crushed stone.

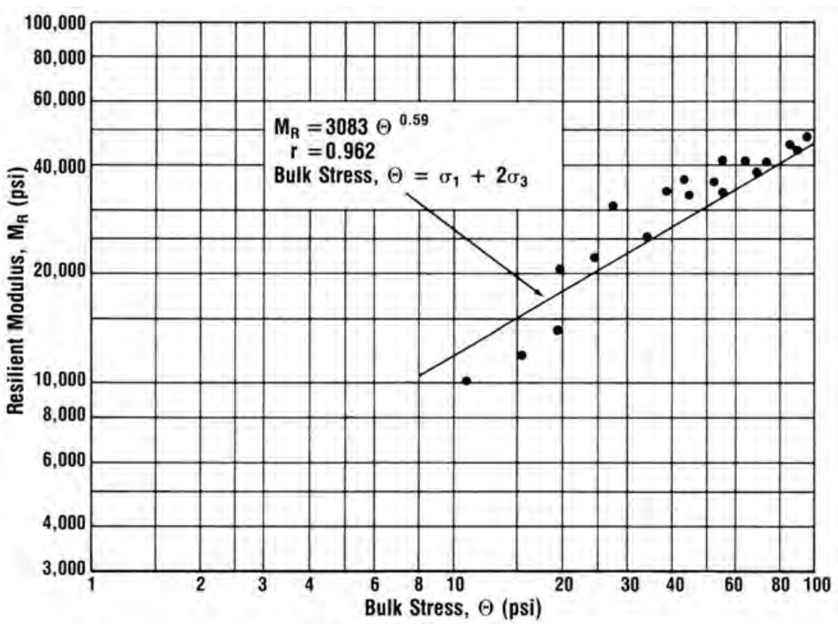


Figure 11.29 Relationship between resilient modulus and bulk stress for a crushed stone.

4. *Type Confining Pressure:* For practical purposes, similar resilient moduli are obtained from repeated load tests performed using constant and variable confining pressure.

5. *Crushed Particles:* For a given gradation, crushed materials provide increased resilient moduli compared to uncrushed materials.

6. *Aggregates Type:* For a given gradation and nature of material (crushed, uncrushed, etc.), material source (limestone, granite, trap rock, etc.) is not a highly significant factor affecting the resilient modulus.

7. *Density:* For a given material, specimen density has only a limited effect on the resilient modulus.

8. *Gradation:* The effects of minor gradation changes are of limited significance. However, the resilient moduli of open graded aggregates, such as AREA No. 4 or AREA No. 5 ballast, tend to be somewhat lower than for conventional, dense graded aggregates.

9. *High Moisture Content:* Moisture contents above optimum tend to decrease the resilient modulus. Moisture sensitivity varies depending upon specific gradations and the amount and nature (primarily the plasticity index) of the minus No. 200 sieve size material (fines). For materials with limited fines, the effect of moisture change is minor. Open graded aggregates that do not contain fines, such as an AREA No. 4 ballast, are practically moisture insensitive.

   For dense graded materials with increased fines content, the effect is more pronounced. Lary and Mahoney[39] developed moisture sensitivity data for several granular bases sampled from typical U.S. Forest Service roads in the Northwest. Regression equations developed from this study indicate that for an initial modulus of 20 ksi, a 1 percent increase in moisture content decreases the resilient modulus from about 1.6 to 0.6 ksi. Based on a comprehensive summary of available resilient data,[34] Rada and Witczak concluded that from a global viewpoint a marked reduction in k_1 (equation 11-11) and MR occurs with increasing degree of saturation.

Typical Theta Model Constants: Typical resilient moduli properties for aggregates for use in the Theta Model are shown in Table 11.7. These data show that as k_1 increases, k_2 decreases as illustrated in Figure 11.30. Higher quality aggregates exhibit larger k_1 values and smaller values of k_2. Typical values of k_1 and k_2 for base and subbase materials presented in the 1986 AASHTO guide[25] are shown in Table 11.8. The effect of moisture on resilient moduli is included in this table.

Stress State: The resilient moduli of aggregates are dependent upon the stress state. However, it is not possible to accurately predict and/or measure the stress state in a flexible pavement aggregates layer. Since aggregates possess little or no tensile strength, it cannot sustain the radial tensile stresses that try to develop in the lower zones of typical layered flexible pavement. Radial compressive stresses are present in the upper zone of the aggregates layer beneath the loaded area. The magnitude of the aggregates layer stress state is primarily influenced by surface loading (load magnitude and contact pressure) and the asphalt concrete (AC) layer

Table 11.7 Typical Resilient-Moduli Property Data to be Used in Equation 11.11[34]

Granular Material Type	Number of Data Points	k_1 (psi) Mean	k_1 (psi) Standard Deviation	k_2 Mean	k_2 Standard Deviation
Silty Sand	8	1,620	780	0.62	0.13
Sand-Gravel	37	4,480	4,300	0.53	0.17
Sand-Aggregates Blends	78	4,350	2,630	0.59	0.13
Crushed Stone	115	7,210	7,490	0.45	0.23

Note: 1. $M_R(\text{psi}) = k_1\Theta^{k_2}$ as defined in equation (11-11)

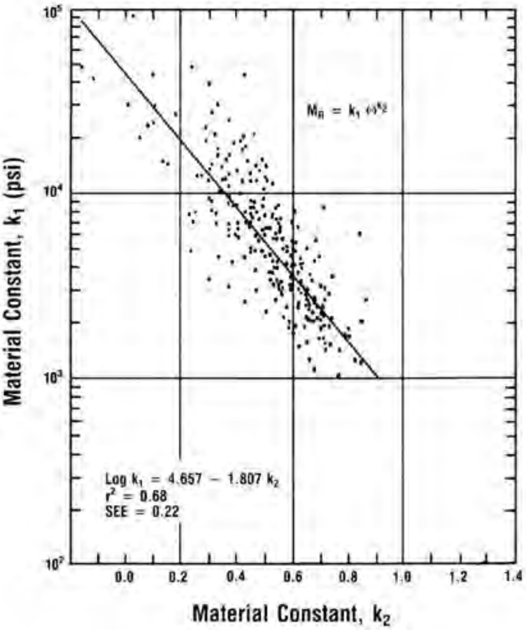


Figure 11.30 Relationship between experimentally derived factors (k_1 and k_2) for the Theta Model

Table 11.8 Typical Values for k_1 and k_2 Defining Resilient Modulus Mr (Equation 11-11) for Unbound Base and Sub-base Materials[25]

Moisture Condition	k_1	k_2
(a) Base		
Dry	6,000 to 10,000	0.5 to 0.7
Damp	4,000 to 6,000	0.5 to 0.7
Wet	2,000 to 4,000	0.5 to 0.7
(b) Sub-base		
Dry	6,000- 8,000	0.4 to 0.6
Damp	4,000- 6,000	0.4 to 0.6
Wet	1,500- 4,000	0.4 to 0.6

Note: 1. The values of k_1 and k_2 are a function of the material quality and compaction level.

thickness and resilient modulus[40] Large values of bulk stress (Θ) are experienced when the AC surface is not present (i.e., when only surface treatment or an unsurfaced aggregates layer is present). Finite element analyses[21,40] indicate that a bulk stress (Θ) in the approximate range from 15 to 50 psi appears to be reasonable. Repeated stress states utilized in laboratory triaxial testing for characterizing the resilient modulus involve using a confining pressure (σ_3) of typically 3 to 20 psi and stress ratios (σ_1/σ_3) varying from 2 to 4.

Design: Elliott and Thompson[41] demonstrated that for a typical range of aggregates materials as expressed by the Theta Model (k_1 = 9,000 psi, k_2 = 0.33; k_1 = 4,000 psi, k_2 = 0.5), the maximum effect on calculated pavement deflection, subgrade stress, and tensile strain in the asphalt concrete is about 10 percent. The nonlinear finite element program ILLI-PAVE was used to predict structural responses. Their analyses of the AASHO Road Test resilient deflection results for Loop 4 also indicated regardless of whether a crushed stone base or a sandy gravel subbase was used the material type *was not* a significant factor with respect to resilient response. This finding is only for resilient pavement response. Both permanent deformation (rutting) and frost action is considerably greater in a sandy gravel base than in a crushed stone base.

Hicks et al[37] considered the effects of percent fracture and gradation of aggregates bases on fatigue performance of pavements. This theoretical study indicated the relative insensitivity of predicted pavement fatigue life and required pavement thickness as influenced by percent fracture and percent fines. Rutting and frost action are very important considerations that were not included in this performance assessment.

For practical structural design of pavements, the use of typical resilient moduli data for generic type aggregates is probably satisfactory. *This does not imply that similar conclusions are valid and that the shear strength, potential for rutting, frost susceptibility and drainability of aggregates are similar*. In fact, many of the factors that have little or practically insignificant effects on resilient behavior significantly influence these important performance factors of aggregates. Hence, the relations presented in the 1986 AASHTO guide between layer coefficients and resilient moduli for aggregates are considered misleading and inappropriate for use in design when used, without modifications, as presented in the 1986 AASHTO guide. This is particularly true when aggregates layer rutting is a major factor influencing pavement performance, such as when low quality or low density aggregates is employed.

Permanent Deformation Behavior: The accumulation of permanent deformation in the aggregates layer(s) contributes to pavement surface rutting or track structure settlement. Typically, maximum rut depths on a pavement surface of ¼ to ½ inch are tolerable with the lower value of rutting being more appropriate for high volume pavements.

The repeated load triaxial test previously described can be used to study rutting in pavement materials in addition to resilient response. At least 5,000 load repetitions are required to establish the trend of permanent deformation as a function of the number of load repetitions. Two permanent deformation models have been widely utilized to characterize for analysis purposes the permanent deformation accumulation in aggregates subjected to repeated loading.

Exponential Model: A typical plot of the log of the permanent strain as a function of the log of the number of load repetitions is shown in Figure 11.31. The general form of the equation for this relation is:

$$\varepsilon_p = AN^b \qquad (11\text{-}12)$$

where

ε_p = Permanent axial strain
N = Number of load repetitions
A, b = Experimentally derived factors from repeated load testing data

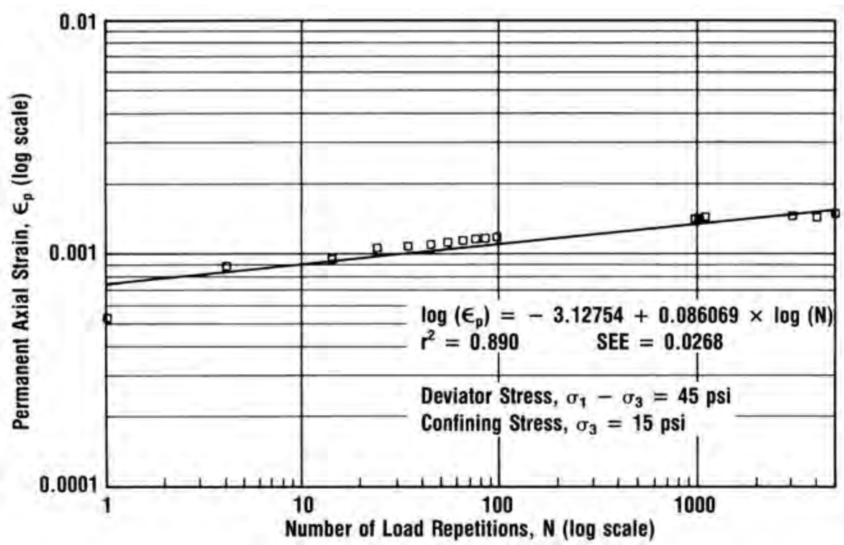


Figure 11.31 Relationship between log of permanent strain and log of load repetitions for a dense-graded crushed stone.

The exponent "b" in the above equation generally varies between 0.1 and 0.2. The coefficient "A" typically is a function of the magnitude of the repeated stress state and varies considerably. The *failure stress ratio* is defined as the repeated deviator stress $\sigma_3 1$ -σ_3 divided by the maximum deviator stress that causes failure. For a failure stress ratio greater than about 0.5 to 0.67, the coefficient "A" in equation 11-12 usually increases rapidly with only a small additional increase in the repeated stress level, as illustrated in Figure 11.32. Limiting the applied stress ratio to acceptable levels is essential in the design of an aggregates base to ensure proper performance. Unstable behavior with respect to rutting of aggregates bases is associated with excessive failure stress ratios.

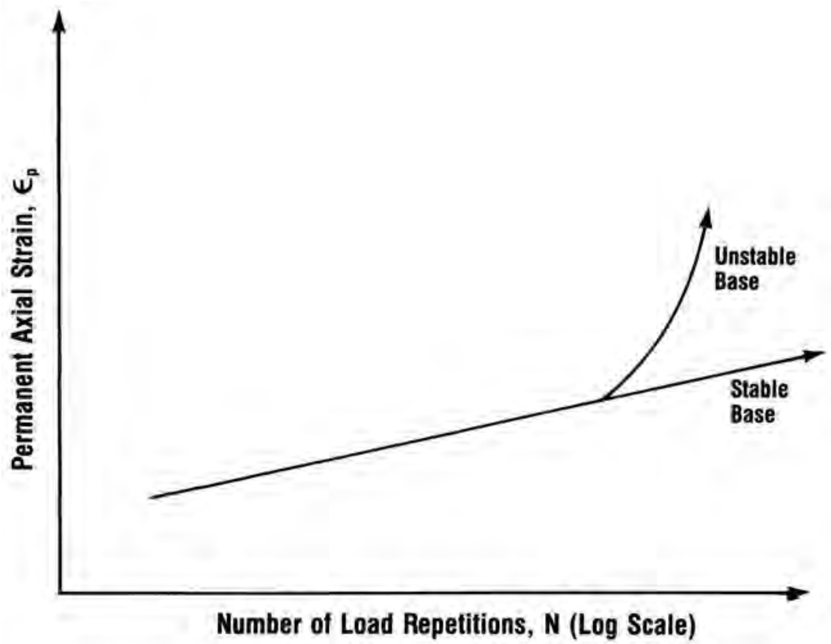


Figure 11.32 Relationship between permanent strain and the number of load repetitions.

Log N Model: Permanent strain of aggregates materials can also be expressed as a function of log N, as illustrated in Figure 11.33. The general form of this relation is:

$$\varepsilon_p = a + b \log N \quad (11\text{-}13)$$

where

ε_p = Permanent strain
N = Number of load repetitions
a, b = Experimentally derived factors from repeated load testing data

Factors Affecting Permanent Strain: For a given aggregates tested under conditions of constant density and moisture content, the permanent deformation response is controlled by the magnitude of the repeated deviator stress $\sigma_1 - \sigma_3$. Figure 11.34 illustrates the typical permanent strain response for a dense graded granitic gneiss having a maximum aggregates size of 1½ inches with 3 percent passing the No. 200 sieve. The maximum principal stress (σ_1) and stress ratio (σ_1 / σ_3) both influence the permanent deformation behavior of aggregates. For a given material and compaction level, permanent deformation increases with decreasing confining pressure and an increasing number of load repetitions and deviator stress.

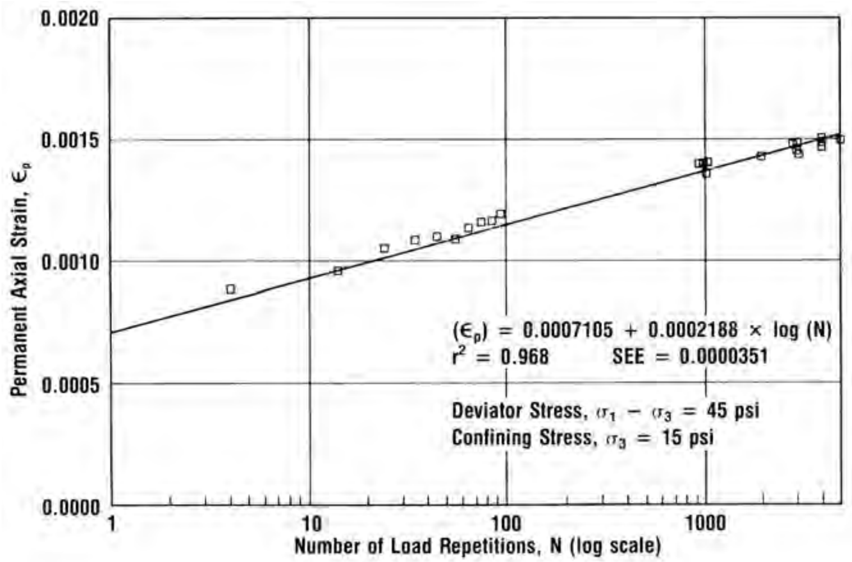


Figure 11.33 Relationship between permanent strain and log of load repetitions for a dense-graded crushed stone.

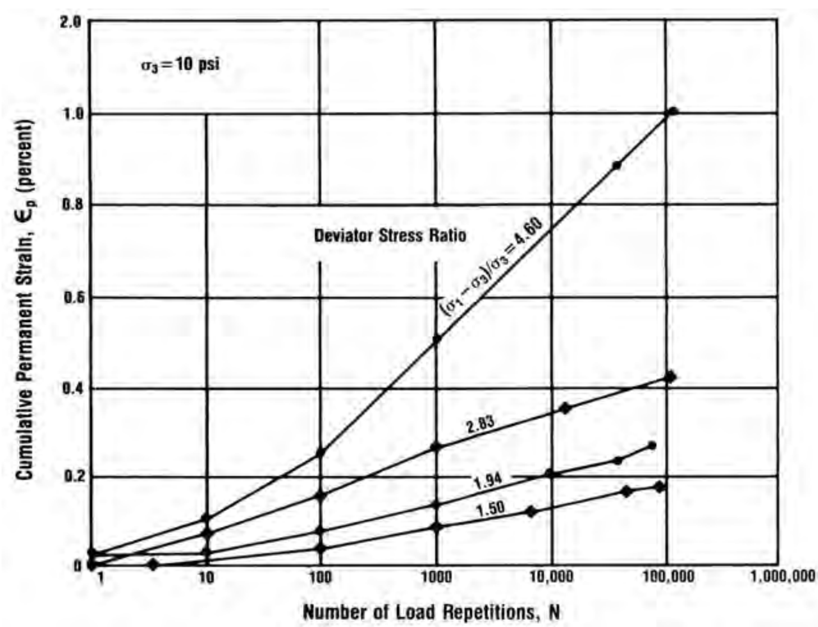


Figure 11.34 Permanent strain response for a dense-graded granitic gneiss.

Permanent deformation accumulation is dependent on the previous stress history to which the specimen has been subjected. If low stresses are initially applied, the effect of increased stress level applications is reduced. However, if large stresses are initially applied, such as those caused by proof-rolling the base, little permanent strain will subsequently develop if lighter loadings (i.e., reduced stress levels) are subsequently applied to the pavement. The higher stress states applied to an aggregates layer control the permanent deformation accumulation for mixed loading conditions when stress states vary from high to low values. A limited number of large stress repetitions due, for example, to heavy logging trucks, can result in large permanent deformation (strain)—refer to Figure 11.34.

In general, the factors previously discussed that increase the shear strength of an aggregates cause a decrease in permanent deformation when subjected to repeated traffic loadings. The dramatic effect of increasing the density of an aggregates base is illustrated in Figure 11.35. Limiting the repeated stresses to about 60 percent of the shear strength of a granular material limits permanent deformation accumulation to acceptable levels as previously discussed.

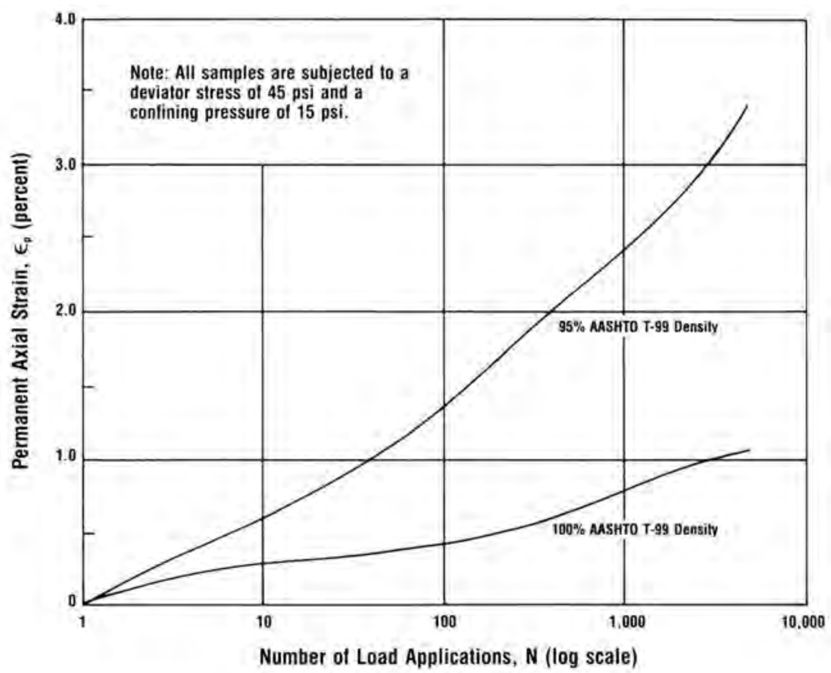


Figure 11.35 Effect of increasing density on an aggregates base.

Summary: The resilient moduli of aggregates bases do not vary greatly for a relatively wide variation in material type. Fine-grained subgrade soils have a significantly greater variation in resilient properties than granular materials. The resilient moduli of granular materials are influenced to a modest degree by gradation, shape/angularity/surface texture (crushed and uncrushed) and moisture content especially for materials having a large amount of fines. The magnitude of the repeated stress state, expressed by the bulk stress, has the most dominating and significant effect on resilient moduli (bulk stress (Θ) is equal to $\sigma_1 + \sigma_2 + \sigma_3$). *Although considerable emphasis has lately been placed on resilient moduli, from a practical viewpoint the permanent deformation characteristics are often more important.*

Improved Resilient Modulus Model

An improved, practical model, however, has been proposed by Uzan[78] that can be developed from the same test results required to develop the Sigma 3 and Theta Models. The Uzan Model gives a higher statistical correlation coefficient and smaller standard error of estimate than these other models.

The Uzan resilient modulus model includes both a theta term and a deviator stress term as follows:

$$M_R = K_3 \theta^n \sigma_D^{n'} \qquad (11\text{-}13)$$

where

K3, n and n' = Constants determined from a statistical correlation using test results.

θ = Bulk Stress $(\sigma_1 + \sigma_2 + \sigma_3) = (\sigma_1 + 2\sigma_3)$ in a conventional repeated load triaxial test when $\sigma^2 = \sigma_3$.

σ_D = Deviator stress $(\sigma_1 - \sigma_3)$.

The Uzan model is frequently utilized to characterize the resilient modulus of granular materials in stress dependent finite element modeling of conventional flexible pavement systems (i.e., pavements having an asphalt concrete surface and aggregates "base/subbase"). Based on finite element structural modeling studies using Georgia Tech Test Pit data, Tutumluer[79] concludes that the Uzan Model gives "*sufficiently accurate results for pavement design and also are practical enough for routine design use*."

Further refinements and modifications in the repeated load triaxial testing procedure should be included in future versions of AASHTO T 294, including the use of axial deformation measurements inside the triaxial call directly on the specimen.

About three-fourths of ballast degradation is caused by aggregates degradation. The abrasion number has been used to predict ballast degradation. The abrasion number equals the L.A. degradation value plus five times the mill abrasion value. Because of the heavy weighting on the mill abrasion value, this test has a significant influence on the abrasion number and hence acceptance or rejection of an aggregates for use as ballast. However, the mill abrasion test, based on the results of a round robin study has problems concerning reliability and reproducibility. As a result, an AREA committee has recommended that the mill abrasion test (and hence the abrasion number) is not an acceptable test for accepting or rejecting an aggregates.

Use of the resilient modulus in the selection of pavement thickness is rapidly gaining popularity among state DOT agencies. As a result, the resilient modulus test is becoming an important one in the transportation industry. Testing details, however, significantly influences the resilient modulus test results. Recent research on resilient modulus testing will do much toward establishing suitable test procedures. Finally, the chapter presents the Uzan resilient modulus model, which is superior to the Sigma 3, and Theta Models given in the Handbook.

Moisture Sensitivity

Introduction: The stress/strain, shear strength and permanent deformation behavior of dense graded crushed stone base with high fines content (minus No. 200 sieve size material) are strongly influenced by moisture content. This type base is described as *moisture sensitive*.

AASHO Road Test: Haynes and Yoder[42] demonstrated that the dense graded crushed stone base used at the AASHO Road Test was quite sensitive to moisture content. Repeated load tests performed at a repeated deviator stress (σ_1 -σ_3) of 70 psi and confining pressure (σ_3) of 15 psi showed that permanent strain accumulated rapidly as the *degree of saturation* increased. The degree of saturation is the volume of water in the voids between aggregates particles divided by the total volume of voids, expressed as a percent. A small increase in water content causes a large increase in degree of saturation. Haynes and Yoder found that moisture sensitivity increased as the minus No. 200 sieve fraction increased from 6.2 to 11.5 percent.

The moisture sensitive nature of the crushed stone base used at the AASHO Road Test has also been demonstrated using the Illinois rapid shear test, as illustrated in Table 11.9. The rapid shear test was performed at a fast strain rate of 17 inches per inch per second. One sample of base from the Loop 1 pavement contained 6.9 inches per inch degree of material passing is the No. 200 sieve. AASHO Road Test Report 5[43] indicates that the average dry density of the crushed stone base was 140.9 pcf and the mean moisture content was 4.2 percent prior to asphalt concrete surface course construction. The crushed stone base experienced seasonal moisture content and density fluctuations at the Road Test. The observed variation in moisture content was from about 4 to 6.5 percent.

Static shear strength tests[10] performed at a slow loading rate do not show the effect of moisture variation with season and are therefore misleading. Repeated load and rapid shear test results, however, show that the moisture sensitivity of dense graded base can be quite pronounced. The high shear strength of dense graded bases is therefore not maintained throughout the seasons of the year in many climatic zones where poor site drainage exists. *Thus, the pavement section may experience significant distress and perhaps even fail during those periods when base course moisture content is high*. At this time, the base has a low shear strength, low resilient modulus and decreased resistance to permanent deformation accumulation. The subgrade is also weak due to moisture content increases and perhaps freeze/thaw effects.

Table 11.9 Rapid Shear Strength Data for AASHO Road Test Crushed Stone Base Having 6.9 percent Minus No. 200 Sieve Meterial[1]

Specimen Conditions			
Moisture Content %	Dry Density (pcf)	σ_3 (psi)	σ_1 @ Failure (psi)
4.6	140.2	6	222
7.0	140.3	6	79
5.2	140.2	10	251
6.6	141.0	10	103
4.2	139.5	20	340
6.8	140.2	20	136

Note: 1. Rapid strain test performed at a strain rate of 16.7%/sec.

Pore Pressure Development: Dempsey[44] utilized a laboratory test box and a test track to study dynamic pore pressure and residual pore pressure development in crushed stone base subjected to repeated loading. Under cyclic loading, significant dynamic and residual pore pressures were generated in the dense-graded aggregates bases. *However, the open-graded aggregates bases did not develop significant levels of dynamic or residual pore pressures when subjected to similar loadings*. The open-graded base studied had a top size of 1½ inches, 0 percent passing the No. 4 sieve, and a permeability in a saturated condition of 0.202 centimeters per second. However, subgrade soil intrusion into the open-graded aggregates base was observed. The occurrence of subgrade intrusion indicates the necessity for a properly designed filter to keep the subgrade and an open-graded base separated. Materials smaller than ⅜ inch in size were found to be susceptible to pumping under various conditions.[44] The design of aggregates drainage systems using filters is described in detail in Chapter 11.

Control of Moisture Sensitivity: Several procedures have been developed for minimizing the moisture sensitivity of aggregates bases.

Gradation: Moisture sensitivity is primarily controlled by the amount and characteristics of material passing the No. 200 sieve. Moisture sensitivity decreases with decreasing amount and plasticity of the fines present. Thus, use of a more open-graded aggregates base decreases moisture sensitivity. In addition, a small decrease in the amount of fines significantly increases permeability, as shown in Chapter 12 and elsewhere.

For the same aggregates source, the rapid shear strength of an open-gradation base is less than the strength of a dense-gradation at optimum water content and maximum dry density. For example, the rapid shear strength of an open-graded crushed stone used by the Pennsylvania Department of Transportation is approximately 125 psi, as shown at the bottom of Table 11.10. A dense-graded aggregates tested near the optimum water content has a strength of 220 psi (refer to Table 11.9). However, the shear strength of the open-graded base does not fluctuate significantly throughout the year as moisture content changes. In marked contrast, the dense-graded material experiences a large decrease in strength as the moisture content increases due to seasonal effects.

Table 11.10 Pennsylvania Department of Transportation Open-Graded Drainage Material: Crushed Dolomite

Sieve	% Passing
1-in.	100
¾-in.	75
½-in.	60
⅜-in.	50
No. 4	25
No. 16	0

Compacted Dry Density: 117 pcf
Moisture Content: Air Dry
Rapid Shear Strength at 16.7%/sec:
$\sigma_1 = 125$ psi at $\sigma_3 = 6$ psi

Fines Modification: The moisture sensitivity of dense-graded aggregates can be modified by the addition of admixtures. Cement and hydrated lime are the most effective, commonly used stabilizers. The objectives of fines modification using admixtures are to reduce moisture susceptibility by immobilizing the fines and reducing frost action potential.

The goal of fines modification is the reduction of the detrimental influence in which excessively high fines contribute toward poor pavement performance. A high fines content causes an aggregates base course to be sensitive to both moisture and frost action. This sensitivity can be minimized by adding a small quantity of stabilizing material such as lime or portland cement, but these materials must be used in moderation to prevent excessive shrinkage, which can lead to cracking of the surfacing.

Lime: Several agencies have modified dense-graded aggregates bases by adding 2 to 3 percent of lime to dense-graded aggregates base. Lime decreases the plasticity and moisture susceptibility of the fines and may, depending upon the mineral composition of the fines fraction, develop significant cementing action. Data shown in Table 11.11 indicate that 3 percent lime modification is effective in significantly improving the performance of dense-graded aggregates having 19 percent fines and a plasticity index of 14. Upon the addition of 3 percent lime, the rapid shear strength increased from 50 psi to 82 psi. For this comparison, the lime modified specimens were not allowed to cure and hence the results are conservative. Permanent deformation behavior under repeated loading also was greatly improved. The compressive strength of the base studied also increased with curing time and hence the fines fraction of this material is lime reactive. Thus, the shear strength and rutting resistance of this base should increase if time is allowed to undergo field curing.

Summary: The use of open-graded aggregates base course gradation specifications and fines modification of dense-graded aggregates bases offer significant potential for reducing aggregates moisture sensitivity, thus improving field performance. If dense-graded, moisture-susceptible materials are utilized, greater AC surface thickness may be required in some climatic zones to assure that repeated load stresses in the aggregates layer during critical seasons of the year are reduced to acceptable levels to control permanent deformation in the base. In contrast, the use of a crushed stone base having low moisture sensitivity and increased rutting resistance permits the use of a thinner AC surfacing, if the AC surface layer fatigue response is satisfactory. Cost comparison studies are required to determine the most cost effective design, which varies depending on traffic conditions, subgrade soils, climatic severity and available materials.

Table 11.11 Lime Treated Crushed Stone Data

Gradation

Sieve	% Passing
¾-in.	100
½-in.	88
No. 4	58
No. 16	34
No. 200	19

Plasticity of Fines

LL = 31
PL = 17
PI = 14

AASHTO T99 Compaction

Untreated: $w_{opt.} = 7.5\%$; $\gamma_D max = 136$ pcf

3% Hydrated Lime Treatment: $w_{opt.} = 8.7$; γ_D max = 133 pcf

Rapid Shear Strength[(1)] @ $\sigma_3 = 6$ psi

Untreated: $\sigma_1 = 50$ psi
Lime Treated (no curing): $\sigma_1 = 82$ psi

Permanent Deformation Response ($\sigma_3 = 6$ psi)

Repeated σ_1 (psi)	Permanent Strain (%) At N = 5,000 Repetitions	
	Natural	Lime Treated
31	0.51	0.14
46	4.0[(2)]	0.13
56	—	0.10
66	—	0.19
76	—	4.0[(3)]

Notes: 1. Performed at a Strain rate of 16.7%/sec
2. At 1,000 load repetitions
3. At 2,000 load repetitions

11.5 Frost Susceptibility

1. Values tied to gradations should be shown
2. Show effect with different soils (Sanders).

Frost action within granular bases and subbases is an important consideration that is all too often neglected. A comprehensive summary of frost action technology for use in roadway design is given in NCHRP Synthesis of Practice No. 26[47] Frost action causes surface heave upon freezing.

Usually important components of differential heave occur, which, if sufficiently severe, result in surface cracking. If freezing occurs slowly, frost action results in thick ice lenses being formed in the frozen zone. During spring thaw, large quantities of water are then released from the frozen zone that can include all unstabilized pavement layers. The release of this water causes a greatly weakened pavement condition that leads to both cracking and surface roughness. After thawing, some residual differential settlement often remains. Spring thaw is thus a critical time in the life of a pavement.

To develop full frost action the following requirements must be satisfied: (1) the material must have a source of capillary water for large ice lenses to form, (2) the gradation of the material must be fine enough to have a depression of freezing temperature in the smaller voids, and (3) the permeability of the material must be high enough to allow relatively free moisture movement to the zone where ice lenses are formed. Particularly frost susceptible subgrade soils include soils with intermediate permeabilities such as silty gravels, silty sands, sandy silts and low plasticity clays. Alligator cracking in pavements has been found to be almost directly proportional to the amount of fines in the base course.[67] Small amounts of alligator cracking were observed when the base had less than 5 to 6 percent fines content.

Laboratory freezing tests that give the heaving rate in millimeters per day of the material are available to characterize frost action potential.[48,49] Laboratory testing to define frost action potential is not a routine procedure. Instead, frost action effects are usually controlled by placing restrictions on the grain size and plasticity of the finer portions of the base.[47]

A commonly used criterion for controlling frost action is the U.S. Army Corps of Engineers' criterion[49] that is given in Table 11.12. Potential heave rates and frost susceptibility classifications developed at the Cold Regions Research and Engineering Laboratory are shown in Figure 11.36. Frost-susceptible materials can be modified as indicated in the NCHRP Synthesis of Practice No. 26:[47]

> "Stabilization is widely used as a method of processing subgrade and base course material to improve their performance under traffic and climatic conditions. Effective stabilization of a frost-susceptible material usually involves (1) eliminating the effects of soil fines by their removal or by immobilization, such as cementitious binding; or (2) reducing the quantity of water available at the freezing plane by blocking migration passages. The commonly used stabilizing additives include portland cement, bitumen, lime and lime-fly ash."

Aggregates products produced with less than 8 percent minus No. 200 sieve size material should not be frost active and do not require special treatment.

Table 11.12 Corps of Engineers' Criteria for Frost Susceptible Soils[49].

Frost Group	Soil Type	Percentage Finer Than 0.002 mm, By Weight	Typical Soil Types Under Unified Soil Classification System
F1	Gravelly soils	3 to 10	GW, GP, GW-GM, GP-GM
F2	(a) Gravelly soils	10 to 20	GM, GW-GM, GP-GM
	(b) Sand	3 to 15	SW, SP, SM, SW-SM, SP-SM
F3	(a) Gravelly soils	>20	GM, GC
	(b) Sand, except very fine silty sand	>15	SM, SC
	(c) Clay, PI>12	—	CL, CH
F4	(a) All silt	—	ML, MH
	(b) Very fine silty sands	>15	SM
	(c) Clays, PI<12	—	CL, CL-ML
	(d) Varved clay and other fine-grained, banded sediments	—	CL and ML; CL, ML, and SM; CL, CH, and ML; CL, CH, ML, and SM

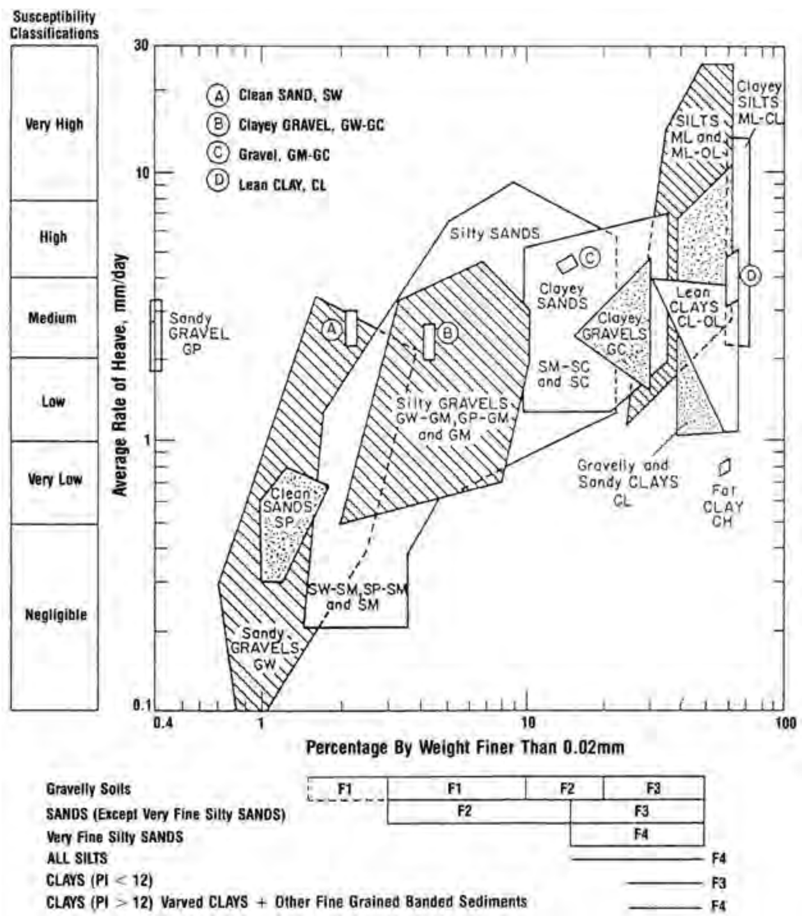


Figure 11.36 Frost susceptibility classification of soils.

11.6 Aggregates Layer Thickness

It is acceptable to perform other methods but the ICAR Mechanistic Design procedure as developed in Project 506 should be the preferred method. The ICAR mechanistic design procedure including transfer functions is expected to become the preferred basis for design.

An appropriate aggregates layer thickness must be established for pavement and railroad applications. Important items to be considered are magnitude and number of loads, subgrade soil characteristics and environmental factors, such as frost action and the occurrence of moisture.

Highway Pavements

Distress Modes: The most common modes of flexible pavement distresses are *rutting and fatigue cracking* of the asphalt concrete surfacing. Fatigue cracking is usually evidenced by alligator or chicken wire type cracking patterns. Fatigue cracking is caused by repeated bending strains induced in the asphalt concrete layer by repetitious bending. Surface rutting under repeated load applications develops as permanent strain accumulates in each layer of the pavement and in the subgrade.

For high-type pavements carrying large traffic volumes, surface rutting generally is limited to a maximum of 0.5 inch For low volume roads, it may be as high as 1 to 2 inches.[25] The thickness of the asphalt concrete surface, aggregates base, and aggregates subbase in conventional flexible pavements and the quality of each material must be adequate to limit the surface rutting to acceptable levels and minimize fatigue cracking of the asphalt concrete layer.

Thermal cracking and frost action are also important mechanisms causing pavement distress. Thermal cracking occurs at low temperatures and causes transverse cracks in the pavement. Low temperature cracking is particularly likely to occur when a hard asphalt cement is used in the asphalt concrete surfacing. The susceptibility of asphalt cements to thermal cracking is discussed in Chapter 13 while frost action was discussed in the previous section of this chapter.

Pavement Thickness Designs: Many organizations have developed pavement thickness design procedures. The Traffic Intensity Category Procedure is patterned after the U.S. Army Corps of Engineers' California Bearing Ratio (CBR) approach.

Traffic Intensity Category Procedure:
Step 1: Evaluate the probable subgrade support.
Step 2: Assign the proper traffic category.
Step 3: Select the appropriate design thickness.

The various traffic intensity categories, as defined by Design Index (DI) values, are described in Table 11.13. The design chart shown in Table 11.14 is used to select the total pavement thickness. Note that the minimum asphalt concrete surfacing thickness increases with an increasing

Table 11.13 Design Index Categories for Traffic[12, 51]

Design Index	General Character	Daily EAL(1)
DI-1	Light traffic (few vehicles heavier than passenger cars, no regular use by Group 2 or 3 vehicles)	5 or less
DI-2	Medium-light traffic (similar to DI-1, maximum 1000 VPD,(2) including not over 10% Group 2, no regular use by Group 3 vehicles)	6 to 20
DI-3	Medium traffic (maximum 3000 VPD, including not over 10% Group 2 and 3, 1% Group 3 vehicles)	21 to 75
DI-4	Medium-heavy traffic (maximum 6000 VPD, including not over 15% Group 2 and 3, 1% Group 3 vehicles)	76 to 250
DI-5	Heavy traffic (maximum 6000 VPD, may include, 25% Group 2 and 3, 10% Group 3 vehicles)	251 to 900
DI-6	Very heavy traffic (over 6000 VPD, may include over 25% Group 2 or 3 vehicles)	901 to 3,000

Notes: 1. EAL = Equivalent 18 kip axle loads in design lane, average daily use over life expectancy of 20 years with normal maintenance.
2. VPD = Vehicles per day, all types, using design lane.

Table 11.14 Basic Design Thickness Table For Temperature Climate[12, 51]

Subgrade Soil		Design Thickness (in.) For Indicated Traffic Intensity Categories					
Class	CBR	DI-1	DI-2	DI-3	DI-4	DI-5	DI-6
Excellent	15	5.0	6.0	7.0	8.0	9.0	10.0
Good	10 to 14	7.0	8.0	9.0	10.0	11.0	12.0
Fair	7 to 9	9.0	11.0	12.0	14.0	15.0	17.0
Poor(1)	3 to 6	13.5	16.5	18.5	20.5	23.0	26.0
Minimum—Any class asphalt surfacing thickness (in.)		1.0(2)	2.0	2.5	3.0	3.5	4.0

Notes: 1. Poor soils should be upgraded or capped with sub-base material to improve support to fair or better class.
2. Use surface treatments, or increase to 1.5 in. including a prime coat on the compacted stone base; if not, mixed asphalt is preferred as the surface.

Table 11.15 Soil Support Categories[70]

General Soil Description	Strength-CBR
Excellent Well-graded, essentially granular, nonplastic soils, may contain some gravel. (AASHTO Groups A-1, A-2)	15 plus
Good Clay gravels, firm sands with some clay. (AASHTO Groups A-1, A-2, some A-3's and A-4's, a few rare A-6's and A-7's)	10-14
Fair Sandy clays, sandy silts, or light silty clays, low in mica, variable plasticity. (AASHTO Groups A-3, A-4, some A-5's, A-6's and A-7's)	6-9
Poor Highly plastic clays, fine silts, very fine or micaceous silty clays. (AASHTO Groups A-5, A-6, A-7, a few A-4's)	5 or less

traffic number, as shown at the bottom of Table 11.14. Subgrade soil classes used in Table 11.14 are defined more fully in Table 11.15.

Asphalt Institute Procedure: The Asphalt Institute design approach[11] is based on elastic layer structural analysis. The resilient moduli of all the paving layers and the subgrade soil are required inputs for The Asphalt Institute's method. The pavement design is based on limiting values of resilient strain. Limiting the bending strain in the asphalt concrete controls fatigue cracking, and limiting the vertical strain on the subgrade attempts to control rutting in the subgrade. The Asphalt Institute design procedure does not directly limit permanent deformation in the layers above the subgrade.

1986 AASHTO Guide: The 1986 AASHTO Guide for Design of Pavement Structure[25] is based on the original AASHO structural number and layer coefficient design philosophy. The 1986 AASHTO guide descriptions for structural number and layer coefficient are Structural Number (SN), an index number derived from an analysis of traffic, roadbed soil conditions and environment that may be converted to thickness of flexible pavements using suitable layer coefficients related to the type of material being used in each layer of the pavement structure.

Layer Coefficient Procedure (a1, a2, a3): The empirical relationship between SN and layer thickness which expresses the relative ability of the material to function as a structural component of the pavement. The SN is numerically equal to the sum of the layer coefficients times the layer thickness for the surfacing, base and all subbases. The 1986 AASHTO guide indicates that the layer coefficients for a particular pavement material can be estimated based on the resilient modulus of that material. Considerable difficulty has been encountered in using the relationships between the layer coefficient and the resilient moduli proposed by the AASHTO Guide. As a result, many agencies still use layer coefficients developed from experience. Layer coefficients given by the AASHTO Guide for aggregates base and subbase vary from 0.14 to 0.06. The dense-graded crushed stone base at the AASHO road test is assigned a layer coefficient of 0.14. High-quality aggregates bases, however, can have layer coefficients as large as 0.18 or more. The AASHO sandy-gravel subbase is characterized by a layer coefficient of 0.11. The minimum layer coefficient of 0.06 is for low quality granular material.

Aggregates Surfaced Roadway Thickness Design: Low volume aggregates roads are sometimes constructed without an asphalt surface layer or a surface treatment. A Design Index category of DI-1 (Table 11.13) is an example of a low volume road. In an aggregates surface road, the aggregates layer must be thick enough to protect the subgrade from excessive stress and the aggregates must possess sufficient stability throughout the climatic seasons to withstand the applied traffic loading. Aggregates surface roads are typically about 6 to 12 inches thick. The larger thicknesses are required for heavier loading conditions and poor subgrade soils, as indicated in Table 11.14. General aggregates gradation and plasticity requirements for surface course applications are presented in AASHTO M 147 and ASTM D 1241 specifications.

Railroad Track Structure

Ballast Thickness Design: Part Two of the AREA manual[5] indicates the following concerning ballast:

> "For over fifty years general railroad construction and maintenance practices have utilized a roadway structure composed of a ballast section of two feet in depth, including both the track ballast and subballast. Experience has indicated that a substantial portion of this ballast depth may be successfully composed of a subballast material, which is less expensive than track ballast if proper engineering designs and standards are observed for selection and installation of the subballast.
>
> The use of subballast is primarily confined to the construction of new tracks or the total rebuilding of an existing roadbed."

Many railroads construct mainline track sections with a 12-inch ballast layer. A reduced ballast thickness of 6 to 8 inches is sometimes employed on tracks with low traffic volume or light loading conditions.

11.7 Crushed Aggregates Shoulder Design

Design

Shoulders are important to the safety, strength and traffic-carrying capacity of highways. Adding crushed aggregates shoulders is credited with significant reductions in accidents as follows:[68] 13 percent for 2-foot wide shoulders; 25 percent for 4-foot wide shoulders, and 35 percent for 6-foot wide shoulders.

Shoulder thickness is important and should be selected to provide adequate and safe support for all types of vehicles, at least for temporary or intermittent use. The AASHTO Position Paper on Shoulder Design[69] recommends that design thickness be based upon "criteria which will reflect the magnitude and frequency of loads to which the shoulder will be subjected." Practices of state or local highway departments that have been found successful in the past can serve as a guide for thickness selection or design. Table 11.16 is provided for general guidance only for thickness design. Subgrade soil categories used in Table 11.16 are defined in Table 11.15.

Crushed stone shoulder aggregates should be placed to the full depth of the adjacent mainline pavement whenever possible and carried all the way out to "daylight" to facilitate surface drainage. When this practice is followed and the shoulder depth exceeds about 8 inches, the crushed stone should be placed in two or more layers. For lower layers a somewhat open-grading is recommended. The material used should not inhibit the passage of water from under the mainline pavement to the side ditches. The top layer should have a dense grading and be impervious with enough fines to knot the coarser particles together and resist both erosion and the abrasive action of traffic.

Materials

Crushed stone shoulder surfacing materials should have a dense gradation and be relatively impervious. The gradation given in Table 11.17 can be used for shoulder construction performed in one lift.

Table 11.16 Soil Support Categories[70]

	Traffic Intensity(2)		
Soil Category(3)	Light	Intermediate	Heavy
Excellent	4 in. (min.)	5 in.	6 in. up
Good	5 in. (min.)	6 in.	7 in. up
Fair(4)	6 in. (min.)	7 in.	8 in. up

Notes: 1. Compacted depths.
2. Traffic intensity often measured by equivalent 18,000 lb axle loads; "Light" traffic includes no more than 10 per day, "Intermediate" from 10 to 100 and "Heavy" over 100.
3. See Table 11.15, "Soil Support Categories"
4. Poor soils should be upgraded to the Fair Category

Table 11.17 Gradation for One Lift Surface Construction—AASHTO Designation: M147-65

Sieve Size	% Passing
	Grading C
1 in.	100
⅜ in.	50-85
No. 4	35-65
No. 10	25-50
No. 40	15-30
No. 200	5-15

Note: Where it is planned that the soil aggregate surface course is to be maintained for several years without bituminous surface treatment or other superimposed impervious surfacing, the engineer should specify a minimum of eight percent passing 0.075 mm (No. 200) sieve in lieu of the minimum percentages shown in Table 1 for grading C, D, or E, and should specify a maximum liquid limit of 35 and plasticity index range of four to nine.

11.8 Geotechnical Structural Applications

Mitchell[52] describes several soil reinforcement techniques that have proved to be effective for soil improvement and ground strengthening. Aggregates materials are extensively utilized in the stone column and reinforced earth construction procedures. Extensive information concerning stone column design and construction has been given by DiMaggio,[53] Barksdale and Bachus[54] and Welsh.[55]

Stone Columns

Applications: Stone columns are compacted vertical columns of crushed stone or gravel usually constructed in soft to firm cohesive soils to improve stability or reduce settlement. Stone columns also are sometimes used to improve silty sands and sands that may have clay layers. The stone columns act as compression and/or shear reinforcement elements. The native soil, when reinforced with stone columns, has higher shear strength and stiffness than the in situ soil. Stone columns are utilized in the United States primarily in cohesive soils to increase stability, bearing capacity and the rate of settlement by providing drainage paths by which water can escape from low permeability soils.

The most common applications of stone columns are to stabilize soft ground located beneath embankments and for landslide stabilization. Stone columns also are used for many other purposes, such as to support heavy tanks, to reduce settlements of structures, and to reduce differential settlement between an existing embankment and an additional embankment placed to construct a new lane. Stone columns also decrease settlement by up to about 50 percent of that which would occur in the unimproved soil. Stone columns are rapidly gaining use in improving ground to resist earthquakes, including reducing liquefaction potential and improving stability.

Design: Stone columns are typically 2.5 to 4 feet in diameter. They usually are installed in a triangular grid pattern on approximately 6- to 9-foot centers. Typically, around 20 to 35 percent of the native soil is replaced with stone. Stone columns have been installed to depths greater than 100 feet. An aggregates blanket 1 to 2 feet in thickness is frequently placed over the area to be improved. The blanket functions as a drainage layer and serves as a working platform distributing the applied loads to soft underlying layers. Usually stone columns are constructed using a uniformly graded crushed stone or gravel varying in size from about ½ to 3 inches.

Construction: Stone columns are formed using a probe having a 65- to 165-horsepower horizontal vibrator located in the bottom and high pressure water jets along the sides. Either the top feed or bottom feed method can be employed to construct the stone column.

Top Feed Method: Using the top feed method, the hole is advanced with the help of the water jets in addition to the vibrator and the weight of the probe. After the hole is formed and cleaned out, stone is dropped from the surface down the hole. During construction by the top feed method, the probe must be left in the hole at all times with the water jets running to avoid hole collapse, which is an important concern using the top feed technique.

Bottom Feed Method: In the bottom feed method the stone is fed to the bottom of the hole through a small tube. The vibrator is left running as the hole is formed and jetting water may or may not be used to help in forming the hole. In the bottom feed method, the hole is supported throughout construction, which is not true for the top feed technique. Using either method, the stone, after being placed in the hole, is densified by the horizontal vibrator in 2- to 4-foot increments as the column is constructed. Pre-augering of the hole is carried out in stiff, cohesive soils using either the bottom or top feed methods.

Wet and Dry Methods: Stone columns can be built using either the wet method, which is most common, or the dry method. In the wet method, large quantities of jetting water are employed in forming the hole. In many instances, the jetting water, which flows out the top of the hole, is environmentally objectionable because of the large quantity of silt and clay suspended in this effluent. The dry method does not use water but may employ air. The wet or dry method can be used in combination with either the top or bottom feed construction techniques.

Earth Reinforcement

Earth reinforcement has been defined[56] as "The inclusion of resistant elements in a soil mass to improve its mechanical properties." Earth reinforcement is presently used routinely for the construction of retaining walls and abutment structures, for repair of slope failures and for support of excavations. The earth reinforcement method of ground improvement often is called Reinforced Earth, which is a trademark of the Reinforced Earth Company. It also is referred to as mechanically stabilized earth and reinforced soil. Figure 11.37 illustrates the concept of retaining wall support using reinforced soil. A high quality cohesionless backfill normally is used having less than about 15 percent fines. Crushed stone, gravel and sand all have been successfully employed. According to Mitchell and Villet:[56]

> "An earth reinforcement system has three main components: reinforcement, backfill or in-situ ground, and facing elements. Both metallic and nonmetallic (geotextiles, plastics) materials are used for reinforcement. In strip reinforcement systems, a coherent, composite material is formed by placing strips in horizontal planes between successive lifts of backfill. Grid reinforcement systems consist of metallic bars or polymeric tensile resisting elements arranged in rectangular grids placed in horizontal planes in the backfill. Wire mesh can be used, in a similar manner, as can continuous sheets of geotextile laid between layers of the backfill.

The facing elements currently used include precast concrete panels, prefabricated metal sheets and plates, gabions, welded wire mesh, shotcrete, seeded soil, masonry blocks and geotextiles. Selection among these depends on type of reinforcement, function and aesthetics."

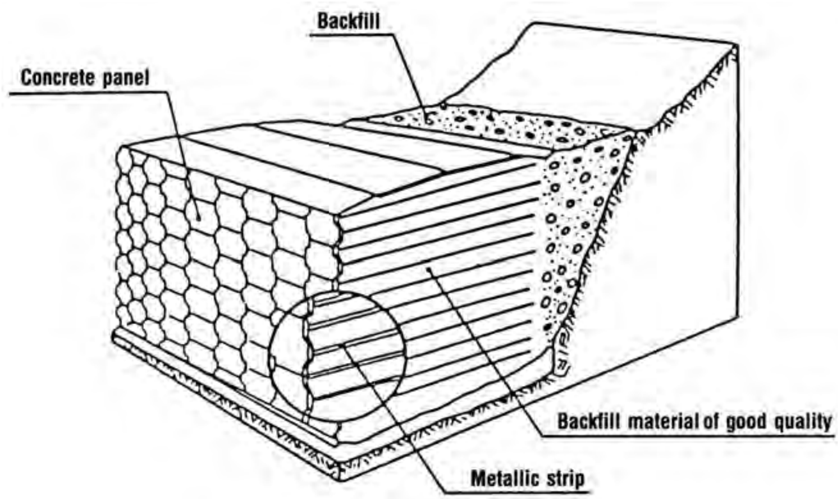


Figure 11.37 Retaining wall support using reinforced soil.[56]

Usually the backfill used with reinforced soil behind a retaining wall is a granular material. Mitchell and Villet[56] state:

> "The use of soils with poorer strength, gradation and plasticity characteristics generally will require more massive, more heavily reinforced, more deformable and more costly structures. Creep and durability problems may be more severe in these soils as well. Nonetheless, use of lesser quality backfills may be possible in many cases."
>
> High-quality backfill should be used when it is available. When it is not, a cost analysis should be conducted to consider the higher cost and potentially poorer performance of a larger, more heavily reinforced structure constructed using the available lower quality soil. The Federal Highway Administration's[57] recommendations for select granular backfill for mechanically stabilized earth wall construction are presented in Table 11.18.

The facing for a reinforced soil wall usually is supported on an unreinforced footing 1 foot wide and 0.5 foot thick, which serves only as a leveling pad. Typical length of reinforcement is about 0.7 times the wall height. When a metallic reinforcement is used, corrosion of the reinforcement over the life of the structure is an important concern. Use of a granular backfill usually significantly reduces the corrosion potential compared to that of a cohesive soil. When a corrosive environment cannot be avoided, use of a high-density polymer grid offers an excellent alternative to metallic reinforcement. If a geotextile is used for reinforcement, long term durability of the fabric should be given careful attention during design.

Table 11.18 Federal Highway Administration Gradation Recommendations for Select Granular Backfill Material for Mechanically Stabilized Earthwalls[57]

Sieve	% Passing
4 in.	100
No. 40	0 to 60
No.200	0 to 15

Note: The backfill shall conform to the following additional requirements:

1. The Plasticity Index (PI) as determined by AASHTO T-90 shall not exceed six.

2. The material exhibits an angle of internal friction of not less than 34° as determined by the standard Direct Shear Test—AASHTO T-236, on the portion finer than the No. 10 sieve, utilizing a sample of material compacted to 95% of AASHTO T-99, Methods C or D (with oversized corrections as outlined in Note 7 of AASHTO T-99) at optimum moisture content. No testing is required for backfills where 80% of sizes are greater than ¾ in.

3. Soundness. The materials shall be substantially free of shale or other soft, poor durability particles. The material shall have a magnesium sulfate soundness loss of less than 30% after four cycles.

4. Electrochemical Requirements. The backfill materials shall meet the following criteria:

Requirement	***ASTM Test Method***
Resistivity > 5000 ohm/cm	*G 57*
pH >4.5 <9.5	
**Chlorides < 100 ppm*	*D 4327*
**Sulfates < 200 ppm*	*D 4327*

**Soils with resistivity less than 5000 ohm/cm but greater 2,000 ohm/cm may be acceptable with these additional requirements. (Electrical properties from FHWA-RD-89-186).*

11.9 Aggregates Surfaced Parking Areas and Walkways

General Considerations

Attractive and economical sidewalks, paths and unsurfaced parking areas can be constructed using construction aggregates. Basic considerations in the selection of suitable aggregates include:

- Ease and safety of walking;
- Resistance to erosion by surface runoff water;
- Drainability; and
- Aggregates cost.

For pathways, walkways, parking areas and similar applications, the ability to walk easily and safely over the surface is an important consideration. If the aggregates is too large and open-graded, the surface is unstable and hence hard to walk on, particularly with high heels. If the aggregates have too many fines, erosion of this material is a problem, especially when placed on a slope.

Gradations: For most applications, a ½ to ¾ inch maximum size aggregates having the gradations shown in Table 11.19 offers a good compromise. Because this aggregates is quite open-graded it drains very rapidly. When the aggregates layer placed is less than 4 inches in thickness, gradation No. 2 in Table 11.9 is a good choice. When gradation No. 2 is used, vehicles may become stuck when the thickness of the aggregates layer is greater than about 4 inches Some maintenance of the aggregates surface is required because it moves around under traffic.

For layers greater than about 4 inches in thickness, gradation Nos. 1 and 3 given in Table 11.19, can be employed. Gradation No. 1 is often preferable to gradation No. 3 since walking on the surface in high heel shoes may be difficult or even dangerous if the larger top size gradation is used. Erosion of finer material from the surface becomes a problem, particularly for gradation Nos. 1 and 3, when slopes are greater than about 3 percent.

When placed on a good subgrade, paths and walkways require an aggregates thickness of only 1 to 2 inches. For an unpaved parking area constructed over a good subgrade, the minimum aggregates thickness is 4 to 6 inches. When necessary, a structural thickness design can be carried out as discussed in Section 11.6.

Campsites: Gradation Nos. 1 and 2 given in Table 11.9 are suitable choices for campsites and similar applications.

Table 11.19 Aggregate Gradations for Walking Surfaces and Parking Areas

	Gradation		
Sieve Size	No. 1	No. 2[(1)]	No. 3
2 in.	—	—	97 to 100
¾ in.	—	100	60 to 90
½ in.	100	90 to 100	—
⅜ in.	90 to 100	40 to 75	—
No. 4	75 to 90	5 to 25	—
No. 8	—	0 to 10	—
No. 10	—	—	25 to 45
No. 16	20 to 40	0 to 5	—
No. 60	—	—	5 to 30
No. 100	10 to 20	—	—
No. 200	5 to 15	—	0 to 15

Note: 1. This is ASTM No. 78 gradation. A slightly more stable surface is achieved when the top size aggregate is limited to ½.

11.10 Miscellaneous Construction Applications

Construction aggregates are suitable for a large number of uses with the imagination of the designer being the only limitation.

Aggregates Exit Pads

The construction of crushed *stone exit pads* is an effective method of reducing the quantity of mud and debris that is deposited on roadways adjacent to construction sites by exiting vehicles. Temporary stone pads, such as those illustrated in Figure 11.38, are constructed using large aggregates particles. The aggregates particles dislodge material from truck tires and prevent the truck from carrying it to the paved roadways. Hence, the use of crushed stone exit pads greatly reduces the quantity of airborne dust and sediment which may be carried to the local community or nearby streams.

Exit pads of crushed stone are placed during the first phase of the development of a new construction site. Crushed stone exit pads are approximately 30 feet in width and 100 feet in length. The depth of the stone is dependent on soil conditions but usually varies from about 4 to 12 inches. An exit pad requires as little as 40 to 60 tons or as much as 500 tons of stone. A No. 2 or No. 3 crushed stone (Table 11.1) has proven to be quite effective in cleaning tires.

Figure 11.38 Crushed stone exit pad at a construction site to reduce pollution.

General Applications

Applications of construction aggregates include landscaping, septic lines, drainage, infiltration basins and liners for drainage ditches to name just a few uses. A number of construction applications of aggregates are given in Table 11.20 together with typical aggregates gradations. Aggregates gradation usage, however, varies throughout the United States and depends upon many factors including aggregates gradation availability, soil type and environment. Local aggregates producers should therefore be contacted concerning the most appropriate gradation for a particular usage.

Table 11.20 Common Construction Application of Coarse and Fine Crushed Stone Aggregates (Courtesy of the Georgia Crushed Stone Association)

Usage	Nominal Aggregate Size	ASTM Designation[1]
Ballast-Concrete-Mudholes-Landscaping-Septic Tank Lines	2 in. to 1 in.	3
Ballast-Concrete-Mudholes-Landscaping	2 to No. 4	357
Ballast-Concrete-Mudholes-Landscaping-Septic Tank Lines-Infiltration Basins	1½ in. to ¾ in.	4
Concrete-Mudholes-Landscaping-Stabilizer	1½ in. to No. 4	457
Type II Backfill Foundation-Septic Tank Lines-Ballast-Infiltration Basins	1 in. to ½ in.	5
Concrete-Asphalt Mixes-Drainage Stone-Septic Tank Lines-Type I Stabilizer-Type II Backfill Foundation-Driveways-Ballast	1 in. to ⅜ in.	56
Concrete-Asphalt Mixes-Drainage Stone-Septic Tank Lines-Type I Stabilizer-Type II Backfill Foundation-Driveways	1 in. to No. 4	57
Asphalt Mixes-Surface Treatment-Concrete-Type I Stabilizer-Septic Tank Lines-Type II Backfill Foundation	¾ in. to ⅜ in.	6
Asphalt Mixes-Concrete-Driveways-Type I Stabilizer-Type II Backfill Foundation	¾ in. to No. 4	67
Asphalt Mixes-Driveways-Concrete	¾ in. to No. 8	68
Asphalt Mixes-Concrete-Drainage-Type I Stabilizer-Surface Treatment-Roofing	½ in. to No. 4	7
Underdrain-Asphalt Mixes-Concrete	½ in. to No. 6	78
Asphalt Mixes–Concrete Drainage-Surface Treatment	⅜ in. to No. 8	8
Asphalt Mixes-Concrete Pipe-Concrete Block-Surface Treatment-Underdrain-Concrete	⅜ in. to No. 16	89
Asphalt-Concrete Block	⅜ in. to Dust	810
Asphalt	No. 4 to No. 16	9
Screening Fill-Backfill-Slurry Seal-Asphalt	⅜ in. to Dust	
Crushed Stone Base-Aggregate Surface-Driveways-Type II Stabilizer-Mudholes-Working Platform	2 in. to Dust	
Concrete Sand: Fine aggregate for Concrete-Filter Sand-Concrete Block-Asphalt-Concrete Pipe	⅜ in. to No. 100	
Graded Rip-Rap[2]: Creeks-Rivers-Drainage Ditches-Earth Dams-Sediment Basins-Shorelines-Slope Protection-Wave Absorbers	6 in. to 48 in.	

Notes: 1. Refer to Table 11.1.
2. Refer to Chapter 12.

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Chapter 12

Aggregates for Structural, Geotechnical and Civil Engineering Applications

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First Edition
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12.1 Introduction

Engineers and builders have several new products and tools available to them in the 21st century. Many of these new products have impressive properties but they also have several common problems. Cost and dwindling supplies of petrochemical based products is a continuing concern. Life span of hydrocarbon "plastic" products and their resistance to weathering, heat-cold cycles and resistance to ultraviolet light are troubling concerns for design engineers, owners and regulatory agencies.

Aggregates and stone products are proven materials that are produced in their home country or region. These mineral products are resistant to weathering and essentially are impervious to ultraviolet light and intense sunlight exposure. Because aggregates, stone, sand and soil are cost effective and locally available, they are the primary materials of design and construction for the structural engineer, geotechnical engineer, civil engineer and builder.

Although aggregates and stone are proven "old-school" materials that are being used in many aspects of modern construction, they also are currently being used in several new and innovative ways. In this chapter, we will discuss some of the older proven applications and some of the newer innovative applications of stone and aggregates materials used in modern design and construction.

12.2 Aggregates Properties for Engineering and Construction

When considering aggregates, properties such as particle size, plasticity, mineral composition, strength, durability and permeability come to mind. Since publication of the first aggregates handbook in 1991, some additional properties of aggregates have become important such as angularity of sand particles, electrical conductivity, thermal conductivity and corrosion potential.

12.2.1 Gradation – Particle Sizes

Aggregates materials are composed of individual particles or pieces of rock. If rock pieces were fine textured, the aggregates would be a silt or sand. If the rock pieces are coarse textured, the material may be gravel, and if it were very coarse, the material would be cobbles or boulders. For hundreds of years, builders or craftsmen called aggregates materials sand, gravel or boulders. When a builder asked for "masonry sand" or "pea gravel," you were expected to "know what he meant." The Aggregates Industry needed a standard way to describe aggregates just like auto mechanics working on mass-produced cars needed to know they were getting a standard sized bolt with a standard thread-type.

The solution to this particle description problem was to measure the diameter of the aggregates particles and describe them by the size of their diameter in inches or millimeters. In theory, this "sizing of particles" concept was good, but in practice it is nearly impossible to measure the diameter of particles less than ⅛-inch diameter without extraordinary, tedious effort including use of a microscope! Another problem — small rock pieces are not round, that is they are not often spherical, so which dimension do you measure?

This is where the sieve (also called a "screen") comes in to provide a tool for particle size measurement. By definition, if a particle passes though a sieve's openings, it is smaller than the sieve size, and if it does not pass through the sieve (i.e., it is retained), it is larger than the sieve size. Use of the sieve does not actually measure the diameter of small pieces of rock, but its use helps approximate their particle size distribution. If hundreds of sieves with each successive sieve just one millimeter larger than the sieve below were used to test an aggregates sample, theoretically the sizes of the aggregates particles in the sample could be determined to within one millimeter. This sieve test would be very impractical to perform and the results would be cumbersome.

In practice, aggregates samples are sieved on several standard sieve sizes (see Chapter 2, Table 2.3 — Selected U.S. Standard Sieve Sizes, Adapted from ASTM E 11), and the percentage of the sample passing each sieve is calculated and plotted on a curve called a *gradation curve* or a *grain size distribution curve* (see Figure 12.1). An aggregates sample consisting primarily of one-sized particle is called uniformly sized or poorly graded (see Figure 12.1 sample 1). Note that the poorly graded sample 1 has a steep, near vertical curve on the gradation plot. A sample having a broad range of particle sizes from fine to coarse grained is called "well-graded" (see Figure 12.1 sample 3). The well-graded sample 3 has a flatter, relatively uniform slope on the gradation plot. If a sample is made up of only two or three particle sizes, it is called a step graded or gap graded sample, see Figure 12.1 sample 2.

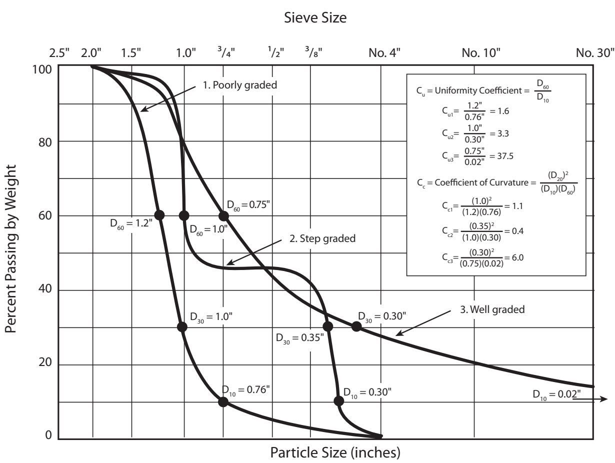

Figure 12.1 Typical Grain Size Distribution Curves

Particle size alone does not sufficiently describe the nature of an aggregates sample. Look at aggregates samples illustrated in Figure 12.2 and 12.3 photographs, see color section, and note that the sample in Figure 12.2 has rounded and sub-rounded particles while the sample in Figure 12.3 has sharp, angular particles. Stone and brick masons in Great Britain call rounded sands "soft sand," and they call sands with sharp, angular grains "sharp sand." These tradesmen are quite proficient in blending soft and sharp sands in their mortar mixes to achieve creamy architectural mortars and "boney" high strength structural masonry mortars.

12.2.1.1 Sieve Analyses

As discussed above, it is impractical to measure particle sizes, so sieves are used to determine the percentage of different sizes that are present in an aggregates sample. To perform a sieve analysis the aggregates sample is shaken and or washed through a series of sieves that are stacked with the largest sieve on top and the sieve with the smallest opening on the bottom. A ⅜-inch sieve is shown in the photograph in Figure 12.4, color section. The sieves used in any particular analysis are commonly determined by specifications set by the agency or owner that will be the end user of the product. The smallest sieve that can practically be used for aggregates particle size analysis is the number 400 sieve because water for washing particles does not easily pass through sieves with openings smaller than 0.04 mm (0.0015 inch). Details of the sieve analysis test are given in ASTM C 136 and D 422 or in AASHTO specifications T 27 and T 88.

After passing an aggregates sample through a series of sieves and drying the particles retained on each sieve, the material retained on each sieve is weighed. Infrequently the weight of sample retained on each sieve is reported as a percentage of the weight of the entire sample. More frequently in engineering and construction practice, the percent finer is calculated for each sieve. The percent finer is the amount of the total sampling that passes a particular sieve. For example if 10 percent of a sample is retained on the 1-inch sieve, 50 percent is retained on the ½-inch sieve, 35 percent is retained on the No. 4 sieve, and 0 percent is retained on the No.200 sieve, then we have 5 percent dust that was washed through the No. 200 sieve (i.e, 100 percent minus 10 percent minus 50 percent minus 35 percent minus 0 percent equals 5 percent passing the No. 200 sieve). The percent finer than the ½-inch sieve in this case is 40 percent (i.e., adding the amounts on each sieve below the ½-inch sieve plus the dust gives 35 percent plus 5 percent equals 40 percent). As shown on Figure 12.1 the grain size curve is plotted as a cumulative percentage from each sieve so that the percentage passing each sieve size is given on the vertical axis and the sieve size opening (on a logarithmic scale so it will fit) is given on the horizontal axis. Although a sieve analysis only determines percentage passing at selected sieve sizes on the grain size distribution curve, this curve is commonly plotted as a smooth curve between points. This practice can lead to problems if few sieves are used to analyze a "step graded" sample, as we shall see below.

12.2.1.2 Analysis of Particles Smaller than the No. 200 Sieve

Although the smallest practical sieve size for aggregates analysis is the No. 400 sieve, the engineering profession has selected the No. 200 sieve as the dividing line between fine sands above and silts and clays below 0.074 mm (0.0029 inch). To determine the grain size distribution curve for particle sizes passing the No. 200 sieve a hydrometer analysis is used. To perform a hydrometer analysis on the fine portion of an aggregates sample, a weighed portion of the fines are split from the main sample and dispersed in water to form a thin slurry or suspension that looks like muddy water. Immediately after the sample is shaken up, a hydrometer is inserted into the suspension to measure its specific gravity in Figure 12.5 (see color section). With time the suspended particles settle to the bottom of the container (ASTM uses a large graduated cylinder), with the large particles settling first and the finer sized particles settling later. By taking hydrometer readings at specified times from initial shaking, the sizes of particles remaining in suspension can be determined by use of Stokes' Law. For details of the hydrometer test, the reader is referred to ASTM D 422 or AASHTO T 88.

The fine particles passing the No. 200 sieve are further classified by determining if they are silt or clay particles. Silt particles under the microscope look just like sand particles, and in fact they are just very fine pieces of sand. Clay particles are much different than silt particles because they have unbalanced electrical charges on their surfaces. These unbalanced electrical charges act like small electromagnets and cause clay particles to attract and hold water molecules. This ability to attract water and form a "sticky" surface is measured in common geotechnical practice by the Atterberg Limits test, using the Liquid Limit (ASTM D-4318) and the Plastic Limit (ASTM D-4318). The plasticity index, calculated as the Liquid Limit minus the Plastic Limit, is high when the clay mineral has a strong attraction to water and it is low when the attraction is weak. When the fines in an aggregates sample consist of medium to high plasticity clay particles rather than silt particles, the resulting strength of the compacted aggregates may be significantly reduced. Clay can coat and stick on sand and gravel-sized aggregates particles adversely affecting their performance in concrete and asphalt products.

12.2.1.3 Use and Evaluation of Particle Size Distribution Curves

As discussed above, aggregates samples may be composed of particles having one, two or three sizes, or many sizes. By visual examination of the grain size distribution curves shown in Figure 12.1 it may be seen by the shapes of the curves that Sample 1 is poorly graded, sample 2 is step graded, and sample 3 is well graded. Federal agencies such as the U.S. Army Corps of Engineers, the Federal Highway Administration, the Department of Energy as well as State Departments of Transportation and building code enforcement agencies have the need to know more about the properties of an aggregates material than whether it passes certain sieves and has adequate soundness. They also may need to evaluate an aggregates sample's application as a filter material, as a base material or a component of concrete or asphalt. To make these determinations they need numerical measures of how well or how poorly a sample is graded and if it is step or gap graded.

For evaluation of grain size distribution curves, there are three measures commonly used to determine how an aggregates sample is graded. These are the "effective diameter," the "uniformity coefficient" and the "coefficient of curvature."

The effective diameter is the aggregates particle diameter where the percent passing on the grain size distribution curve is 10 percent passing. The effective diameter is frequently referred to as D_{10}, which means the effective particle size diameter where 10 percent of the sample by weight is smaller. The effective diameter is used to estimate relative permeability of clean sand filters by use of the Hazen Equation (1911) and is a rough indicator of relative permeability of sandy soils. The Hazen Equation is given below as Equation 12-1. This equation may be used for estimating purposes, but is not recommended for design. For design purposes, the engineer should use field and or laboratory tested values of permeability.

$$K = C\,(D_{10})^2 \qquad (12\text{-}1)$$

where

the effective diameter is in centimeters, C is a coefficient between 100 and 150, and the permeability, K has units of cm/sec.

The uniformity coefficient C_u (or Coefficient of Uniformity, see Chapter 2) is a measure of the uniformity of the grading of an aggregates sample. It is defined as the ratio of the diameter at 60 percent passing, D_{60}, to the diameter at 10 percent passing, D_{10}. A uniform sized, poorly graded aggregates has values of D_{60} and D_{10} that are close together so the ratio D_{60}/D_{10} will be close to one (see the calculation box in Figure 12.1). Poorly graded sample 1 has a uniformity coefficient of C_u = 1.6. Well graded samples have values of D_{60} and D_{10} that are far apart so the ratio D_{60}/D_{10} will be much greater than one (see the calculation box on Figure 12.1). Well-graded sample 3 has a uniformity coefficient of C_u = 37.5. Step graded aggregates often have uniformity coefficients that are low, such as sample 2 in Figure 12.1. It also is possible to have step-graded materials that have three or four steps spaced such that they give uniformity coefficient values that are nearly the same as uniformly graded materials. This is possible because the uniformity coefficient only considers two particle sizes, D_{60} and D_{10}. When designing graded filters for dams, it is very important to be sure that each successive granular layer retains the previous layer to avoid "piping," that is internal erosion of layers which may eventually lead to failure of a dam. Step-graded aggregates have "holes" in their grading which could cause piping to occur even if the numerical values of the uniformity coefficient of the layers are appropriate. The fact that an aggregates is step-graded can be observed by studying the grain size distribution curve of the material. By looking at sample 2 gradation curve in Figure 12.1, it is obvious that it is a stepped curve and not a smooth curve like sample 3. It also is apparent by comparing curve 2 to both curves 1 and 3 that the step-graded sample has steep steps that are not parallel to the smoother curves. To avoid having to visually compare all the aggregates grading curves for a project, several coefficients have been developed and used. The most common of these gradation curve shape measures of smoothness is called the "coefficient of curvature."

The coefficient of curvature, C_c is defined as:

$$C_c = (D_{30})^2 / (D_{10})(D_{60}) \qquad (12\text{-}2)$$

Samples that are step-graded have lower values of the coefficient of curvature. In Figure 12.1, the step-graded sample 2 has a C_c value of 0.4, while the well-graded sample 3 has a C_c of

6.0. Samples with coefficients of curvature between 1 and 3 normally are considered to be well graded so long as they have uniformity coefficients above 4 for gravels and 6 for sands.

12.2.2 Strength of Aggregates Materials

There is some confusion in the industry about the strength, that is, shear strength, of granular materials. To listen to some people, you would think that certain aggregates have inherent friction angles (ϕ), when they ask, "Give me some aggregates for retaining wall backfill. It has to be free-draining, and have a 34 degree friction angle." How do you go out into the yard and pick out a pile of 34-degree friction angle aggregates material?

We need to set the record straight. The strength of a granular material depends on its compacted density, stress-state, surface roughness of particles, the nature of the "fines" that coat particles and fill voids between particles, on the aggregates' mineral composition, and most importantly, it depends on the laboratory test used to determine the friction angle. A granular soil's shear strength is measured by its friction angle. The friction angle (commonly referred to by the Greek letter ϕ, called phi) used to measure an aggregates' shear strength is more appropriately called the "angle of internal friction." The equation of soil shear strength that is used to determine the angle of internal friction is the Mohr-Coulomb Equation (see Figure 12.6). In general, the denser an aggregates material is compacted the greater its shear strength. The Mohr-Coulomb equation and the concept of aggregates material shear strength will be discussed in greater detail in the following sections.

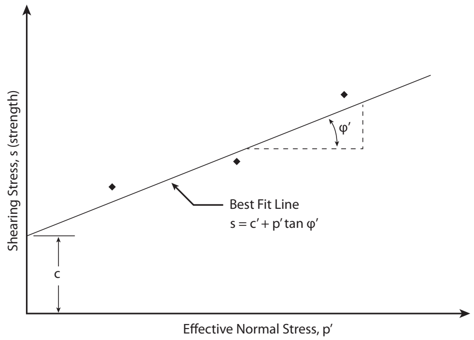

Figure 12.6 Mohr-Coulomb Failure Equation

12.2.2.1 The Angle of Repose

Before discussing the angle of internal friction of granular soil, we need to say a few words about the angle of repose. If a granular soil is poured from a large hopper or conveyor belt on to the ground, it forms a cone shaped pile. As the aggregates pours on to the pile it slides down until a stable slope angle is formed. The material may temporarily form a steeper angle, but as additional material is added to the pile, it eventually slides down into a stable slope. The acute angle formed between the ground surface and the pile slope is called the *angle of repose* (see Figure 12.7, color section). Since the pile formed by pouring granular material onto the ground represents a very loose state of the material, the angle of repose is approximately equal to the minimum angle of internal friction of the material. It may be possible to deposit a sandy soil under water to obtain a looser state with a lower internal angle of friction than the angle of repose, but it only will be marginally looser.

12.2.2.2 Shear Strength of Granular Materials

The strength of granular materials is determined by doing tests where samples are loaded and movement or displacement of the sample is measured. Test sample stresses are calculated by dividing the applied loadings by the area of the sample. To determine sample strains developed in response to test loadings, the sample "length" is divided by the sample deflections. Finally sample stresses are plotted versus sample strains (or deflections in the direct shear test) to generate a stress-strain curve. Figure 12.8 is an example of a typical stress-strain curve.

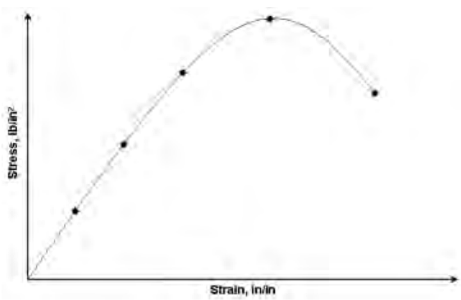

Figure 12.8 Typical Stress-Strain Curve

Often it is assumed that the aggregates sample has failed when the stress-strain curve reaches a peak value. This is not always the case. To determine the sample failure condition from the stress-strain curve requires knowledge of the definition of failure for the case being considered. Another factor in determining the failure condition is the shape of the stress-strain curve, which varies depending on sample density, and the stresses (i.e., confining stresses) applied to the sample during loading. A discussion of the affect of sample density and test confining stresses is given below.

12.2.2.3 Loose versus Dense Samples

When a dense sample is loaded, the stress-strain curve has a relatively steep slope and a peak value of sample strength is achieved as illustrated in Figure 12.9. After the peak strength is reached, the sample strength decreases with increasing strains until a limit or ultimate strength value is achieved.

When a loose sample is loaded, the stress-stain curve is not as steep as the dense sample, and a peak value is not developed. Instead, the loose sample slowly gains strength until it reaches a limit value as shown in Figure 12.9. For a given granular sample tested to large strains, both the dense and the loosely compacted samples approach the same strength, which is referred to as the residual or ultimate strength.

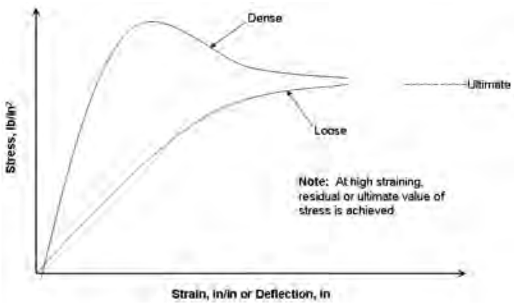

Figure 12.9 Stress-Strain Curves for Loose verses Dense Samples

12.2.2.4 Affect of Confining Stresses

Granular backfill behind a 10-foot high retaining wall may have lateral or confining stresses of approximately 3 pounds per square inch (i.e., about 430 pounds per square foot). The same granular material in a 300-foot high dam would experience much higher confining stresses, about 100 pounds per square inch. High stresses cause the angular pointed parts of the aggregates particles to crush causing the material to be much more plastic under loading. The result is that very high confining stresses cause a dense granular material to have a smoother stress-strain curve without a peak seen at lower "usual" construction stresses, see Figure 12.10. The graph in Figure 12.10 was developed by assuming that the loading is vertical and the confining stress is horizontal, the ratio of the vertical stress to the horizontal stress is plotted on the vertical axis to normalize the data and allow a comparison of results of testing at different confining stresses.

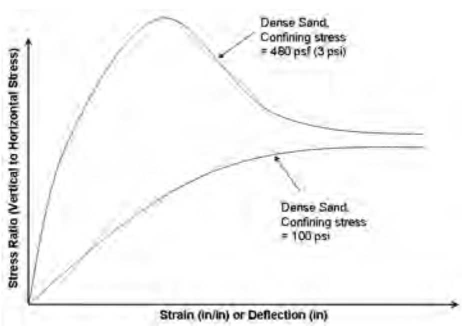

Figure 12.10 Dense Sand, Lower verses Very High Confining Stress

From study of Figure 12.10 it can be seen that dense sands behave like loose sands when confining stresses are very high. Similarly, as illustrated in Figure 12.11, at very low confining stresses loose granular materials exhibit peak stresses like dense material do at normal stress levels.

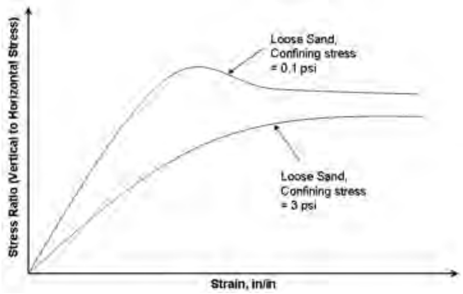

Figure 12.11 Loose Sand, Low versus Very Low Confining Stresses

12.2.2.5 Selecting Strength Test Points and Drawing the Mohr-Coulomb Failure Envelope

After testing of samples is completed and stress-strain curves have been plotted, shear strength parameters cohesion C and angle of internal friction ϕ of the sample are determined by plotting the Mohr-Coulomb diagram. If samples are dense, the design requirement may be to use the peak or residual strength values from the stress-strain curve. If the sample stress-strain curve does not have a peak, or if the design requires very low displacements or strains, design strength values may be selected from stress-strain curves at 5 or 10 percent strain.

After strength values are selected, they are plotted on the Mohr-Coulomb diagram as shown in Figure 12.12. Data plotted on Figure 12.12 is from the same series of tests with one set of points representing peak values and the other set of points representing residual or ultimate values. Note the large difference been the internal friction angles using peak values versus residual values even though all data was developed from the same tested material.

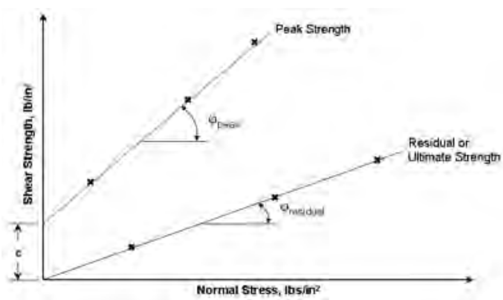

Figure 12.12 Mohr Coulomb Failure Lines

Large differences in strength also result from using different testing methods on the same aggregates sample. For example, the greater compaction energy resulting from the Modified Proctor test give higher strengths than the Standard Proctor test for the same aggregates material, see Figure 12.13 below.

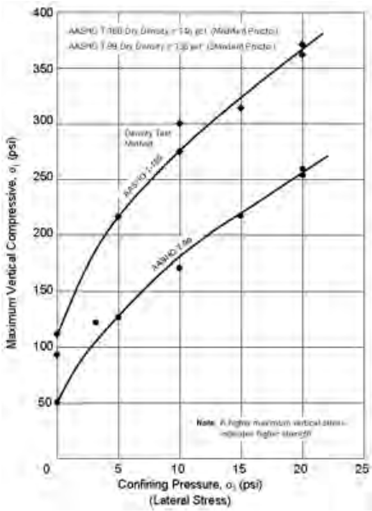

Figure 12.13 Relationship of Soil Strength to Compaction Density

12.2.3 Durability

Aggregates must be durable and remain sound for the design life of any structure that includes the aggregates as an integral part of the support mechanism. Other chapters in this handbook discuss the durability of aggregates and stone in their uses in concrete and asphalt. When used in geotechnical and civil engineering applications, aggregates have to resist wind and water erosion, physical break down by loading of traffic or structures, breakdown due to weathering (which includes wetting and drying), thermal stresses from sun exposure and freeze/thaw cycles. When used in dams, levees and water resources structures, aggregates must be tested and pass requirements set by the U.S. Army Corps of Engineers, the Bureau of Reclamation, and numerous state agencies. When used as paving base course materials, aggregates must meet requirements of the American Association of State Highway and Transportation Officials (AASHTO). Most building agencies and building code officials use the International Building Code (IBC) which references ASTM Standards to test for aggregates soundness. The usual tests check an aggregates' resistance to abrasion, to wetting and dry, and to freeze/thaw cycles, most of these tests are similar to the following typical ASTM standard aggregates tests used for concrete aggregates:

- C 88 Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
- C 131 Test Method for Resistance to Degradation of Small-Size Coarse Aggregates by Abrasion and Impact in the Los Angeles Machine
- C 142 Test Method for Clay Lumps and Friable Particles in Aggregates
- C 535 Test Method for Resistance to Degradation of Large-Size Coarse Aggregates by Abrasion and Impact in the Los Angeles Machine
- C 666 Test Method for Resistance of Concrete to Rapid Freezing and Thawing

In Chapter 2 the Los Angeles Degradation Test, ASTM C131, (commonly referred to as the L.A. abrasion test) is described. This test often is used to determine the resistance of aggregates to abrasion and impact by use of pulverizer balls in a large tumbler. Figure 2.3 in Chapter 2 shows a sketch of an L.A. abrasion test machine.

12.2.4 Permeability

The term permeability, also called hydraulic conductivity, is a measure of a granular material's ability to resist fluid flow. If the permeability of a granular material is low (i.e., slow flow), the amount of water that can flow through the material under a given hydraulic gradient is low. The fluid flow equation that defines permeability is called Darcy's Law (or D'Arcy's Law). Darcy's Law is expressed in Equation 12-3.

$$Q = K\,i\,A \qquad (12\text{-}3)$$

where

Q = flow in volume of liquid per unit time
K = the material's permeability in length per unit time
i = the hydraulic gradient which is unitless
A = area (perpendicular to the flow vector)

Permeability may be determined in natural granular deposits by field tests, in relatively undisturbed or processed samples by laboratory tests, or it may be estimated by correlations to grain size distributions by using approximate equations such as Equation 12-3 above. Discussion of field and laboratory permeability testing is included below.

12.2.4.1 Field Permeability Measurements

Permeability or hydraulic conductivity tests performed in the field on a single well or test hole are performed by "packer tests" used to isolate an interval in the test hole, by slug tests where water is added to the test hole, and by pumping tests were water is removed from the test hole. To test a greater portion of the ground and get a better measure of the tested stratum's permeability, water is pumped from a well (or pumped into the well) with several nearby monitor wells used to measure the radius of influence of the drawdown "cone of depression." Tests conducted with multiple pumping wells in the region of study and several monitor wells around each pumping well are considered to be the best tests although such tests are obviously more expensive than tests conducted on a single well.

Aggregates materials are used in the annular space between the well screen and the perimeter of the well's borehole to prevent caving of the borehole and to keep the formation (i.e., native soils) was washing into the well screen. Formation materials that wash into the well screen can form a "cake" on the screen clogging it and preventing flow. The aggregates used acts as a filter to prevent well screen clogging.

12.2.4.1.1 Well Filter Pack Design

To prevent formation materials from washing into a well's screen, the aggregates material installed around the well screen, called the "well filter pack" has to been designed based on the grain size curves of the formation materials. For an illustration of a grain size curve, please refer to Figure 12.1.

After samples of all soil types from the depth interval of the well screen are tested for grain size distribution, and all of the grain size curves are plotted, the filter pack's grain size is selected on the basis of the finest formation materials encountered. The United States Environmental Protection Agency ("Manual of Water Well Construction Practices," Report No. EPA-570/9-75-001, 156 pages, 1975) and the Johnson Division Manual ("Ground Water and Wells," Edward E. Johnson, Inc., St. Paul, Minn., 440 pages, 1966) recommend designing a monitor well's filter pack based on the selected finest formation soil's D_{30}. To design a filter pack's grain size distribution, the filter material's D_{30} size is selected to be 3 to 6 times larger than the formation materials D_{30}. If the formation material is fine grained and uniform, the factor 3 is recommended. If the formation is coarser grained and nonuniform, the factor 6 is recommended. In either case, the filter pack materials should have a uniformity coefficient of between 1.0 and 2.5. The filter pack's gradation curve should be smooth and uniform with no step grading, and should be approximately parallel to the formation material's grain size curve. For further information on water well or monitor well aggregates "filter pack" design, review of the latest edition of the Johnson Division manual is recommended.

12.2.4.2 Laboratory Permeability Tests

There are two primary tests used for measuring the permeability or saturated hydrologic conductivity of an aggregates sample, 1. constant head test and 2. the falling head test.

The constant head test is used primarily for cleaner, coarse-grained samples. In the ASTM constant head test procedure (ASTM D 2434, Permeability of Granular Soils, Constant Head), it limits the test to disturbed samples of granular soil with not more than 10 percent of the sample passing a No. 200 sieve. ASTM also insists that the sample permeability be tested for laminar and not turbulent flow at a standard temperature of 68 degrees Fahrenheit (20° C). If actual field or design conditions vary from these test assumptions, the design engineer or scientist may have to modify the laboratory permeability value to adjust for flow conditions and viscosity of water at lower or higher temperatures.

Permeability associated with the Darcy Flow Equation is not only dependent on the granular sample; it also depends on the fluid's properties. If a fluid other than water is flowing in the porous aggregates material, the permeability value that should be used in Darcy's Flow Equation is different. For example a sand and gravel sample would have a lower test value of permeability if light-weight oil rather than water were used. This is because oil is more viscous than water, and less oil than water would flow through a sample in a give time period. Since the hydraulic gradient and sample size (both on the right side of the equation) would be the same, the only thing that could reduce to match a reduced flow (on the left side of the equation) would be the permeability, see Equation 12-3 above.

The falling head test and the falling head test with sample backpressure are used for aggregates samples with more than 10 percent fines or for fine-grained samples. The falling head test is much more complicated than the constant head test and several things can go wrong such as release of air bubbles from the flowing liquid as the head water pressure declines. The falling head test can be done with both with rigid and flexible sample enclosures, although most low permeability tests are currently performed in accordance with ASTM D 5084, which uses a flexible wall permeameter. Conduct of permeability tests on fine-grained samples should be done by a certified testing laboratory that has considerable experience in this type of testing.

Preliminary values of permeability for use in estimating or early preliminary design are given below in Table 12.1. Actual laboratory or field-tested permeability values should be determined for use in preliminary and final design.

Table 12.1 Typical Values of Aggregates Permeability

General Description(s) of Aggregates	Permeability, cm/sec
1. Clean Gravel	1 to 100
2. Sand Gravel Mixture, Clean Sand	0.001 to 1
3 Silty Fine Sands, Silts, Clayey Silty Sand, Clayey Silt	0.000001 to 0.001 ($1 X 10^{-6}$ to $1 X 10^{-3}$)

12.3 Subsurface Drainage, Graded Filters and Drains

Aggregates materials are used in subsurface drainage applications adjacent to building foundations, beneath and adjacent to roadway paving, in drainage systems of dams and levees, in drainage systems behind retaining walls, beneath and adjacent to water and wastewater treatment tanks, beneath and adjacent to swimming pools, and hundreds of other drainage applications too numerous to list here. The primary purpose of aggregates drainage systems is to collect and convey water. In many applications, aggregates are used in conjunction with perforated pipes to increase the flow capacity of the drainage system, and sometimes it is used by itself. An aggregates drain installed in a trench without a pipe often is generically referred to as a "French Drain."

The terms filter and drain often are used interchangeably although there is a slight difference in the implications of each term. In the process of draining water from a soil mass, three objectives must be met. The native material or fill soil that is required to be drained also should be protected from loss of material or piping. The filter or drain should have permeability greater than the protected soil to allow free movement of water and prevent excessive backup of water in the protected soil. And finally the filter or drain should have adequate discharge capacity to drain the required flow of water from the protected soil mass. The USACE in Appendix D, "Filter Design" of their manual EM 1110-2-1901 refer to these three requirements as the *stability requirement*, the *permeability requirement* and the *discharge capacity requirement*. The USACE describe as filter as a layer of granular material that must meet the stability and permeability requires. They explain that filters generally accept flow that enters the filter perpendicular to the interface between the protected soil and the filter and are not primarily concerned with flow capacity. A drain must meet the same requirements of stability and permeability as a filter plus drains must additionally have adequate discharge capacity to carry the required flow to an outlet or discharge point. So the difference between a filter and a drain is the requirement that the later must "drain" to a discharge point with adequate capacity to prevent the system from backing up into the protect soil mass.

If design of aggregates drains were concerned only with water flow capacity, an equation such as Darcy's Flow Equation could be used to design the required cross section and slope or "fall" of the drain. The primary complications of aggregates drainage design involve clogging of drainage materials with fine sand and silt, and an associated problem in the adjacent soil mass called "piping." Piping is migration of fines from a soil mass in an uncontrolled manner that results in internal erosion of the soil and potentially causes a failure of the soil mass.

To prevent an aggregates filter or drain from excessive clogging there are three basic approaches:
1. Design the aggregates drain as a "graded filter,"
2. Wrap the aggregates drain with geotextile filter fabric that is designed to filter the fines while maintaining adequate permeability, or
3. Over-size the drainage pipe and aggregates layer to maintain enough residual flow capacity to function after they are "silted-in" with fines. This third approach should include a maintenance plan to periodically inspect and replace the drainage system if it becomes totally clogged. In design of dams this third approach is discouraged. In design of commercial structures and for some levees, the third drainage alternate is sometimes considered in life cycle cost analyses that include maintenance and early replacement costs.

12.3.1 The Stability Requirement

The concept of designing an aggregates filter or drain to protect the adjacent native soil or fill soil from internal erosion or "piping" involves design of a "graded filter." Design of a graded filter is a process of comparing the size of holes or voids between particles of the filter layer material to the size of smaller particles from the protected soil that are trying to wash through the aggregates drainage-filter layer. The first issue is to estimate the size of voids between particles of a given size. If the aggregates material is assumed to be a collection of uniformly sized spheres, the size of the voids would be equal to approximately one-sixth the diameter of the particles. Since real aggregates samples are distributions of sizes as illustrated by their grain size distribution curves, engineering organizations such as the United States Army Corps of Engineers, the United States Department of Agriculture's Natural Resources Conservation Service, and the former United States Bureau of Reclamation have performed testing to determine graded filter criteria. Each agency has published aggregates filter design guides, which will be summarized and described below.

12.3.2 The USACE Design Method (1993)

The USACE Filter Design Method is included as Appendix D to their Engineering Manual EM 1110-2-1901. Filter and drain designs based on this method must meet the three design requirements: 1. Stability, 2. Permeability and 3. Discharge capacity.

The *stability requirement* is intended to protect the base or "protected soil" from erosion and piping, and to protect the filter layer from clogging. The term filter is used when referring to design of both filters and drains. As a convention, "d" refers to the protected soil, and "D" refers to the filter material.

To design the gradation of a filter to meet the stability requirement, the Corps method gives an eight-step process:

1. Perform a grain size analysis of the soil to be protected. Do not test just one sample. Characterize the range of soil types present on the site by geologic and geotechnical evaluation of the materials, and run several tests to establish a family of gradation curves that are representative of the soils requiring filter protection. From the family of curves determine the filter D_{15} that will protect the finest base material.
2. If the base soil has no gravel, that is material retained on a No. 4 sieve, then go to step 4.
3. Adjust gradation curves for base soils with gravel.
   a. Calculate a correction factor by dividing 100 by the percent passing the No. 4 (4.75 mm) sieve.
   b. Multiply the percentage passing each sieve smaller than the No. 4 sieve by the correction factor. The corrected percentage passing the No. 4 sieve is now 100 percent.
   c. Plot the "corrected" percentages passing to obtain a new gradation curve.

d. Use the adjusted gradation curve to determine the percent passing the No. 200 sieve (0.075 mm) for use in determining the Base Soil Category in the Table 12.2 given below.

4. Determine the base soil category using the adjusted percent passing No. 200 sieve.
5. Determine the maximum D_{15} size for the filter using Table 12.3 below. Do not use a maximum D_{15} size smaller than 0.20 mm.
6. For adequate filter permeability, select the minimum D_{15} ∃ (3 to 5) $d_{15\ max}$, but not less than a particle size of 0.1 mm.
7. Select the maximum particle size of the filter at 3 inches (75 mm) and the maximum percentage passing the No. 200 sieve at 5 percent. The filter material passing the No. 40 (0.425 mm) must have a plasticity index (PI) of zero.
8. Finally design the filter gradation with limits that conform to the maximum and minimum values determined in steps 5, 6, and 7 above. Plot the limit values on a gradation curve graph, connecting all of the maximum and all of the minimum values with straight lines. A selected filter gradation should have a relatively uniform grain size distribution curve with no "gap or step" grading. To prevent segregation during construction of coarse graded filters, it is suggested that the limits given in Table 12.4 be used. For additional guidance and examples of filter design, please refer to USACE Engineering Manual EM 1110-2-1901.

Table 12.2 Categories of Base Soil Materials

Base Soil Category	Percentage Finer Than the No. 200 (0.075 mm) Sieve
1	> 85
2	40 – 85
3	15 – 39
4	< 15

Table 12.3 Criteria for Filters

Base Soil Category	Base Soil Description, and Percent Finer than No. 200 Sieve*	Filter Criteria**
1	Fine silts and clays; more Than 85% finer than No. 200	D_{15} # (9) d_{85}***
2	Sands, silts, clays, and Silty or clayey sands 40 to 85% finer than No. 200	D_{15} # 0.7 mm
3	Silty and clayey sands and gravels; 15 to 39% finer than No. 200 sieve	D_{15} # {[(40-A) / (40 -15)] [(4 d_{85}) - (0.7 mm)] + 0.7 mm}† ††
4	Sands and gravel with less than 15% finer than the No. 200 sieve	D_{15} # (4 to 5) d_{85}‡

* *Category designation for soil containing particles larger than the No. 4 sieve (4.75 mm) is adjusted to 100% the No. 4 sieve as described in step 3 above.*

** *Filters should have a maximum particle size of 3 inches (75 mm) and a maximum of 5% passing the No. 200 (0.075 mm) sieve with a fines plasticity index of zero. To have sufficient permeability, filters should have a D_{15} size equal to or greater than 4 times D_{15} but no smaller than 0.1 mm.*

*** *When 9 times d_{85} is less than 0.2 mm, use 0.2 mm.*

† *A = percentage passing the No. 200 sieve after any adjustment of gradation.*

†† *When 4 times d_{85} is less than 0.7 mm, use 0.7 mm.*

‡ *In category 4, the D_{15} # 4(d_{85}) criterion should be used for filters beneath riprap subject to wave action and drains which may be subject to violent surging and/or vibration.*

Filter criteria outlined in Tables 12.2 and 12.3 above are applicable for all soils including cohesionless soils, cohesive soils and even dispersive clay soils. Dispersive clays are clays that lose their cohesion when exposed to water with dissolved minerals and salts of a particular chemical composition that requires special testing to determine. After the dispersive clays loose cohesion and disaggregate, they become highly susceptible to internal erosion and piping. To design filters for dispersive soils requires special laboratory pinhole and filter tests plus additional study of the soil's chemical properties. Relative to dispersive clay soils, study of the technical paper "Filters and Leakage Control in Embankment Dams," by Sherard and Dunnigan (1985) is suggested in EM 1110-2-1901.

Table 12.4 D_{10} and D_{90} Limits to Prevent Segregation of Coarse Graded Filters

Minimum D_{10}, mm	Minimum D_{10}, mm
< 0.5	20
0.5 - 1.0	25
1.0 - 2.0	30
2.0 - 5.0	40
5.0 - 10.0	50
10 - 50.0	60

To design a graded filter to meet the *permeability requirement* the water must flow more quickly through the filter than through the protected base soil. In other words, the permeability of the filter must be greater and remain greater (during the life of the facility) than the permeability of the protected soil. To meet the permeability requirement, the filter should be designed to have a grain size distribution that satisfies Equation 12-4.

$$(D_{15}\text{, size filter material}) / (d_{15}\text{, size protected soil}) \exists 3 \text{ to } 5 \qquad (12\text{-}4)$$

This proportion of the 15 percent size of the filter material to the 15 percent size of the protected soil is intended to maintain filter permeability approximately 9 to 25 times greater than the protected soil. A minimum permeability ratio of five is preferred by USACE, although they suggest that protected soils with a wide band width of gradations may be protected with a filter having a permeability ratio as low as three. In cases where the permeability ratio is very important, or in cases of filter applications where drainage of the filter layer is not important (implying that this ratio may be ignored), further study and testing of protected soil and filter permeability is suggested.

To design a graded filter to meet the *discharge capacity requirement*, the USACE suggests that the filter be designed for sufficient flow capacity to comply with Darcy's Law, and they include an example drain design in Chapter 8 of EM 1110-2-1901.

12.3.3 The NRCS Design Method (1994)

The Natural Resources Conservation filter and drain design method was developed as a result of an extensive laboratory filter study conducted by the Soil Conservation Service Soil's Lincoln, Nebraska Soil Mechanics Laboratory from 1980 to 1985. Currently NRCS's filter design material is included in Part 633 of the National Engineering Handbook, Chapter 26, "Gradation Design of Sand and Gravel Filters."

Comparing the USACE Design Method discussed above in section 12.3.2 with the NRCS Design Method discussed in this section shows many similarities. In fact a direct comparison of the USACE eight-step method with the NRCS 12-step method shows that the Corps eight steps are nearly identical to the first eight steps of the NRCS method. Where the two methods are identical, reference will be made to section 12.3.2 to avoid duplication of equations, tables, etc.

The NRCS 12 filter design steps are given below:

1. This step is identical to the Corps Method in section 12.3.2, plus the consideration that the base soil with the largest D_{15} be used for drainage design purposes.

2. Same as step 2 above in 12.3.2.

3. Same as step 3 above in 12.3.2.

4. Same as step 4 above in 12.3.2. The table used is identical to 12.3.2.1.

5. Same as step 5 above in 12.3.2. The table used is identical to 12.3.2.2. But then NRCS adds the following material: "If desired, the maximum D_{15} may be adjusted for certain noncritical uses of filters where significant hydraulic gradients are not predicted, such as bedding beneath riprap and concrete slabs. For fine clay base soil that has d_{85} sizes between 0.03 and 0.1 mm, a maximum D_{15} of less than or equal to 0.5 mm is still conservative. For fine grained silt that has low sand content, plotting below the "A" line, a maximum D_{15} of 0.3 mm may be used."

6. For adequate filter permeability, select the minimum $D_{15} \exists (4)\ d_{15\ max}$, but not less than a particle size of 0.1 mm. Similar to USACE, but the Corps uses $D_{15} \exists (3 \text{ to } 5)\ d_{15\ max}$.

7. The width of the allowable filter design band must be kept relatively narrow to prevent the use of possible step or gap-graded filters. Adjust the maximum and minimum D_{15} sizes for the filter band determined in steps five and six so that the ratio is five or less at any given percentage passing of 60 percent or less. This additional filter criterion to prevent gap-graded filters is summarized below in Table 12.5. The NRCS says that gap-graded filters can be detected by visual inspection of the grain size distribution curve and that requirements of step 10 (which is similar to USACE step eight) should prevent aggregates segregation during construction. This is where NRCS expands their method significantly beyond

the USACE method to include additional checks to avoid step or gap-graded filters without relying on visual inspection of the grain size curves. They suggest that these additional steps are required to develop project filter specifications.

First to avoid gap-graded filters, calculate the ratio of the maximum D_{15} to the minimum D_{15} sizes from steps five and six. If this ratio is greater than five, adjust the maximum and minimum values so that this ratio is not greater than five. If the ratio is less than five, no adjustment is required. Label the maximum D_{15} size as Control Point 1 and the minimum D_{15} size as Control Point 2. Guidance on adjustment of final minimum and maximum D_{15} is given below:

a. Locate the design filter band at the maximum D_{15} side of the range if the filter will be required to transmit large amounts of water thus functioning as a drain. Using the maximum D_{15} size as a control point, calculate a new minimum D_{15} size by dividing the maximum D_{15} size by five. Label the maximum D_{15} size as Control Point 1 and the new minimum D_{15} size as Control Point 2.

b. Locate the band at the minimum D_{15} side of the range if it is likely there are finer base materials than those sampled and tested, and filtering of fines is the most important function of the aggregates zone. Using the minimum D_{15} size as a control point, calculate a new maximum D_{15} size by multiplying the minimum D_{15} size by five. Label the new maximum D_{15} size as Control Point 1 and the minimum D_{15} size as Control Point 2.

c. It is important to locate the maximum and minimum D_{15} sizes within the acceptable range of sizes determined in steps five and six above, so that a standard, available aggregates gradation (i.e., available product) is locally obtainable from a commercial source. Locate a new maximum and minimum D_{15} size within the permissible range to coincide with commercially available material. Check to make sure that the ratio of these D_{15} sizes is five or less. Label the new maximum D_{15} size as Control Point 1 and the new minimum D_{15} size as Control Point 2.

8. The designed filter band should not have an extremely broad range of particle sizes to prevent the use of step or gap-graded filters. Adjust the limits of the design filter band so that the coarse and fine sides have a coefficient of uniformity ($C_u = D_{60} / D_{10}$) of 6 or less. The width of the filter band should be such that the ratio of maximum to minimum diameters is less than or equal to five for all percent passing values of 60 percent or less.

Additional guidance for step eight filter design criteria are given by NRCS as follows:

Initially design filter bands determined by step eight will have C_u values of six. For final design, filter bands may be adjusted to a steeper configuration with C_u values less than six, if needed. This adjustment is acceptable as long as other filter and permeability criteria are satisfied.

Calculate a maximum D_{10} value equal to the maximum D_{15} size divided by 1.2. (The factor 1.2 is based on the assumption that the slope of the line connecting D_{15} and D_{10} should be on a coefficient of uniformity of about six.) Calculate the maximum permissible D_{60} size by multiplying the maximum D_{10} value by six. Label this maximum D_{60} size as Control Point 3.

Determine the minimum allowable D_{60} size for the fine side of the band by dividing the determined maximum D_{60} size by five. Label this minimum D_{60} size as Control Point 4.

9. Determine the minimum D_5 and maximum D_{100} sizes of the filter according to Table 12.6. Label the minimum D5 size as Control Point 5 and label the maximum D_{100} size as Control Point 6.

10. To minimize segregation during construction, the relationship between the maximum D_{90} and the minimum D_{10} of the filter is important. This segregation control requirement is the same as the USACE requirement that uses Table 12.4. To use Table 12.4, take the value of D_{10} determined above in step eight and select the maximum D_{90} and label this size as Control Point 7.

11. Connect Control Points 4, 2 and 5 to form a partial design for the fine side of the filter band. Connect Control Points 6, 7, 3 and 1 to form a design for the coarse side of the filter band. These coarse and fine curves form a preliminary design for a filter band. Complete the design by extrapolating the coarse and fine curves to the 100 percent finer value and determine the percent finer values for standard sieve sizes.

12. Design filter-drains adjacent to perforated pipe to have a D_{85} size no smaller than shown in Table 12.7. For critical drainage structures where high gradients or rapid gradient reversal (i.e., surging) is likely, it is recommended that the D_{15} size of the filter material surrounding the pipe be no smaller than the pipe's perforation size.

Table 12.5 Other Filter Design Criteria

Design Element	Criteria
To prevent Gap-graded filters	The width of the designed filter band should be such that the ratio of the maximum diameter to the minimum diameter at any given percentage passing value at or below 60% is # 5.
Filter band limits	Coarse and fine limits of a filter band should each have a coefficient of uniformity of 6 or less.

Table 12.6 Maximum and Minimum Particle Size Criteria for Filters

Base Soil Category	Maximum D_{100}	Minimum D_5
All categories of soil	Maximum particle size 3 inches (75 mm)	0.075 mm (No. 200 sieve), or percent fines equals 5%

Note: The minus No. 40 (0.425 mm) material for all filters must be nonplastic as determined by the Atterberg Limits test described in ASTM D4318.

Table 12.7 Criteria for Filters Used Adjacent to Perforated Collector Pipe

Description of Drain Type	Filter Material Criteria
Noncritical drains where surging or gradient reversal is not anticipated	The filter D_{85} must be greater than or equal to the pipe's perforation size.
Critical drains where surging or gradient reversal is anticipated.	The filter D_{15} must be greater than or equal to the pipe's perforation size.

12.3.4 The "Traditional" USBR Method (1947)

One of the early graded filter criteria was reported by USBR in 1947. You might be wondering why this older method has been included here when newer methods are available. This earlier method is simpler and easier to use, and proves useful for smaller "non-critical" commercial applications requiring graded filters and drains.

The USBR defined the grain size distribution required by the filter material to keep native soil from being eroded into the filter material by two ratios. The first ratio R_{50} is defined as the ratio of D_{50} of the filter material to D_{50} of the protected soil and the second ratio R_{15} is defined as the ratio of D_{15} of the filter material to D_{15} of the protected soil. Then USBR defined the requirements for these ratios as follows:

1. If the filter material has a uniform grain size distribution (i.e., poorly graded) with a C_u of three to four, then the ratio R_{50} of the filter to the protect soil should be between five and 10.
2. If the filter material is well graded (i.e., non-uniform distribution) with subrounded grains, then the ratio R_{50} should be between 12 and 58, and the R_{15} should be between 12 and 40.
3. If the filter material is well-graded with angular particles then the ratio R_{50} should be between nine and 30, and the R_{15} should be between six and 18.

After giving the three filter requirements listed above the USBR gave a rather lengthy note of an exception: "If the material to be protected ranges from gravel, with over 10 percent larger than the No. 4 sieve, to silt with more than 10 percent a No. 200 sieve, limits should be based on the sample fraction passing the No. 4 sieve. Maximum size of filter material should not exceed 3 inches, and filters should not contain more than 5 percent passing No. 200 sieve. Grain size curves of the filter material and the soil to be protected should be approximately parallel in finer ranges of sizes." This last restriction often is found in specifications for design of graded filters. There are many additional requirements that may be added to prevent "holes" in the filter gradation caused by "gap" or step graded materials. The simplest solution to this problem is to visually inspect the grain size distribution curves to see if they are parallel and to see if they include any undesired "steps."

If clay soils are present in the soil to be protected, many specifications suggest that clay floc sizes or a multiple of the maximum clay floc size be used in the graded filter design (clay floc sizes are estimated by hydrometer tests that are run without dispersants or anti-flocculating agents). If the results of standard grain size analyses are used for graded filter design ("standard" meaning they are performed including the standard hydrometer test for determination of the distribution of clay particle sizes, i.e., a deflocculated sample), the resulting filter gradation will be too fine to drain the protected soil. This explains the minimum particle size criteria given in many filter design guides. Please refer to sections 12.3.2 and 12.3.3 for additional filter design requirements for filters or drains installed on or in soils that included clays.

12.4 Highway, Rail and Airfield Applications

12.4.1 General Considerations

Highway, rail and airfield projects include drainage structures, retaining wall structures, erosion control structures and deep foundation supported structures. Use of aggregates in these applications is discussed in Sections 12.3, 12.5, 12.7 and 12.8. The primary topic to be discussed in this section will be aggregates used as paving base, sub-base and subgrade improvement applications. With national requirements that infrastructure be improved in the 21st century, such as TEA-21 in the United States, billions of dollars are being spent on re-constructing or building new roadways, airports and rail facilities. These projects will need tremendous amounts of aggregates that will be required to meet local, state and federal requirements.

12.4.2 Paving — Aggregates Base and Sub-base

Paving design was once a relatively simple procedure of determining asphalt or concrete paving thickness, aggregates base course thickness and aggregates sub-base course thickness to support a given design traffic based on a subgrade soil characterized by laboratory testing. Early paving design methods included considerations of climate, design life (usually 20 years), initial costs, maintenance costs and "ride-ability" or smoothness of the paving surface. These paving design methods were highly empirical and were based on results of road tests conducted in the 1950s. For details of these paving design methods, we suggest the Asphalt Institute Paving design guide or the AASHTO 1993 Paving Design guide.

Currently paving design is undergoing an extensive revision to make use of computer analyses and structural mechanics. This new AASHTO paving design method is called MEPDG or the Mechanistic Empirical Paving Design Guide. The MEPDG is more like structural design where stiffness and deflection of paving layers is considered. It also is rather complex, not completely calibrated and incorporated into use in all 50 AASHTO states. We will not attempt to discuss details of the MEPDG here, and suggest the reader contact their State Department of Transportation or the AASHTO website for details.

To perform paving design for a roadway or an airport runway, or to check support provided for ties and rails, we need to characterize the strength or stiffness or "paving support properties" of the aggregates base, the aggregates sub-base and the subgrade soil. Paving design is a layer design procedure where the layers are "stronger" from the roadway surface to the soil subgrade. So the paving is stronger than the aggregates base, the aggregates base is stronger than the aggregates sub-base, and the aggregates sub-base is stronger than the subgrade soil.

Another consideration of paving design is cost. The cost of each paving layer normally increases from the subgrade to the top of the paving surface. Assuming that each alternate paving design provides proper ride, minimum maintenance and a suitable design life, it is generally cost effective to minimize the thickness of upper asphalt or concrete paving layers and maximize the thickness of lower aggregates layers to obtain the required section strength.

Since the aggregates base is required to be stronger than the aggregates sub-base, the base material normally consists of more costly crushed aggregates such as crushed limestone. The sub-base aggregates is normally an uncrushed sand and gravel of adequate soundness that requires less processing and is less costly to produce than crushed stone base material.

The strength of aggregates base and sub-base layer materials commonly are tested in a certified materials laboratory on samples provided by suppliers. Representative subgrade soil bulk samples obtained along the paving or rail alignment are used for laboratory testing of the subgrade strength. Depending on the state or agency that regulates paving design, the CBR (California Bearing Ratio, ASTM D 1883) or the R-value test (Resistance R-value, ASTM D 2844) are required to be performed to characterize strength of the base, sub-base and subgrade materials. For details on testing of aggregates and soils by the CBR or R-value test, please refer to ASTM standards.

Typical examples of required properties of aggregates base and sub-base materials are given in Table 12.8.

Table 12.8 Typical Properties of Aggregates Base and Sub-base Materials

Sieve Sizes	Base Type 1 (clean base), Percent Passing	Open Graded Base (very clean), Percent Passing	Sub-base Type A (fairly clean), Percent Passing
2 ½ - inch, (63.5 mm)	—	—	100
1 - inch (25 mm)	100	100	70 - 100
3/4 - inch (19 mm)	80 – 100	90 - 100	—
3/8 - inch (9.5 mm)	—	20 - 55	—
No. 4 (4.75 mm)	30 – 60	0 - 10	25 - 100
No. 10 (2.0 mm)	20 – 45	—	--
No. 40 (0.425 mm)	—	—	5 - 50
No. 200 (0.074 mm)	3 – 10	0 - 2	0 - 10
Two Fractured Faces	50% or more	100%	—

Notes: Fractured faces tests performed on material retained on the No. 4 sieve, the base course materials should have an Aggregates Index of 35 or less and their fines should have a liquid limit of 25 or less and a plasticity index of 6 or less. The Sub-base material passing the No. 40 sieve should have a liquid limit of 30 or less and a plasticity index of 6 or less.

12.5 Retaining Wall and Foundation Applications

12.5.1 Progress in Using Aggregates for MSE Retaining Walls

In the past few decades, use of aggregates has advanced well beyond the standard of construction industry practice used for most of the 20th century. In general, standard practice for aggregates use was to place it as backfill for transmitting loadings to concrete or steel retaining walls. Aggregates also were used as a drainage material or ballast, but not as the primary load carrying structure.

A major change in the application of aggregates to construction of retaining walls was the introduction of modern mechanically stabilized earth (MSE) retaining walls in the early 1970s.

In the 18th, 19th and early part of the 20th century, retaining walls were large masses of concrete or stone referred to as "gravity" retaining walls. Gravity retaining walls resisted lateral earth pressures by virtue of their self-weight as shown in Figure 12.14. These walls were so heavy that the soil's lateral earth pressure could not push them over, and they were designed so that their weight was great enough and their base width large enough to resist over-turning moments generated by earth pressures and surcharge loadings.

During the 20th century, the reinforced concrete cantilevered wall was developed as shown in Figure 12.15. The cantilevered wall used the strength of reinforced concrete to contain a mass of soil on its base. The weight of the soil over the cantilevered wall's base resisted the lateral earth pressure's overturning moment, which was applied to the cantilevered stem of the wall system. This was a considerable improvement over the gravity retaining wall, because the weight of the earth itself was used to help resist lateral earth pressures, and the amount of steel and concrete used in wall construction was minimized.

In the early 1970s, the ancient idea of soil reinforcement by use of tree limbs and reeds was made new again by introduction of steel reinforced earth by the Reinforced Earth Company. This reinforced earth product was a patented system that consisted of flat strips of deformed steel in granular backfill. Use of reinforcements in soil, now called mechanically stabilized earth (MSE), was a further improvement in retaining wall technology because now the reinforced soil itself resisted lateral earth pressures without need for the strength of reinforced concrete as shown in Figure 12.16. Today there are several alternate methods of reinforcing soil including steel strips, steel grids, polymer sheets and polymer grids. Many manufacturers around the world provide reinforcement and wall facing MSE systems.

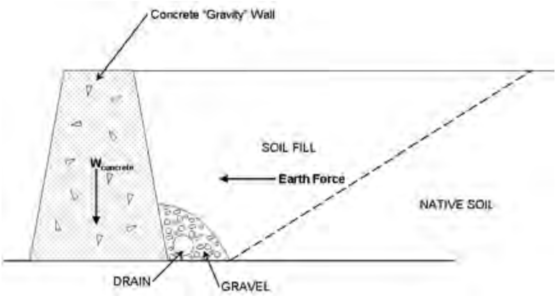

Figure 12.14 Concrete Wall Weight Resists Overturning Earth Pressure

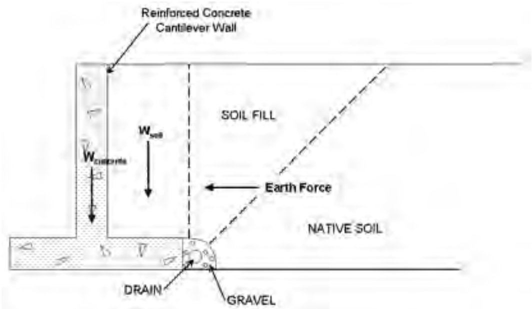

Figure 12.15 Cantilever Soil and Concrete Weight Resists Overturning Earth Force

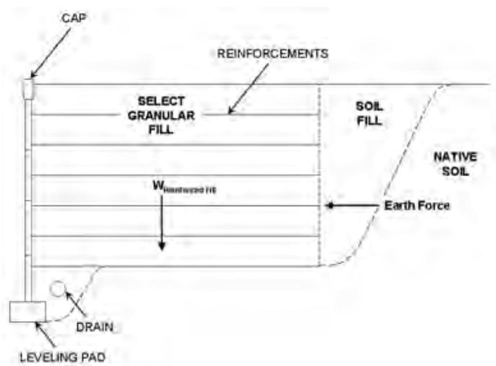

Figure 12.16 Reinforced Soil (MSE) Overturning Earth Force

Precast panels shown on the surface of the MSE wall system in Figure 12.16 are used to prevent surface sloughing of backfill materials and terminate reinforcements. These precast panels and their leveling pad (which looks like a footing but is actually a level surface to start placement of panels) do not resist lateral earth pressures, that is done by the reinforced soil mass. Precast panels are not required on the surface of MSE walls. Wrapped wire mesh reinforcement with and without shotcrete is often substituted for panels on MSE walls in non-architectural or temporary applications. A completed MSE retaining wall with textured and painted precast panels along I-25 in New Mexico is shown in Figure 12.17 (see color section).

The use of MSE walls as retaining structures saves costs of concrete, forming, reinforcing steel placement and tying, and concrete finishing. As a result of these and other savings, MSE walls are cost effective as long as high-quality granular fill material is available for use as backfill. MSE wall cost savings are even greater when wall heights exceed 10 feet or where special foundation treatment or use of deep foundations is required to support a concrete retaining wall.

Some MSE system salesmen suggest that their walls can be built using native clayey soils or weathered clay shales as reinforced backfill. Many wall failures have been reported where unsuitable clayey backfill materials were used to construct MSE walls. Such clayey materials might work for 3- to 5-foot high "garden walls," but they are not recommended for projects requiring structural walls. For structural applications on building or highway projects, the use of a high quality, durable, well-drained, easily compacted, non-corrosive, well-graded, granular backfill material is required. Since reinforcements have to interact with the granular backfill material in friction and passive modes of resistance, a material with high friction characteristics is specified and required.

When galvanized steel reinforcements are used, the backfill must be non-corrosive to prevent excessive loss of reinforcing strength with time. To determine the corrosion potential of an aggregates backfill material requires that five electro-chemical tests be conducted on representative backfill samples. These five tests are: 1. Electrical resistivity which is a measure of the resistance of the material to electrical current flow, 2. pH which is a measure of the acidity of the material, 3. Chlorides content which is a measure of the amount of chloride salts in the material, 4. Sulfates content which is a measure of the amount of sulfate salts in the material, and 5. Organic Content which is a measure of organic compounds in the material that can decompose with time causing increases in soil acidity.

As an example, AASHTO specifications for MSE granular backfill materials are described in Publication No. FHWA-NHI-00-043, "Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines, March 2001," a summary of AASHTO MSE aggregates backfill requirements is given in Table 12.9 below.

Table 12.9 MSE Wall Backfill Requirements per AASHTO

Select Granular Material for MSE Reinforced Zone	
U.S. Sieve Size	**Percent Passing**[a]
102 mm (4 inches)[a,b]	100
0.425 mm (No. 4)	0 – 60
0.075 mm (No. 200)	0 – 15

Plasticity Index (PI) shall not exceed 6

$\Phi_{peak} \geq 34$ degrees

a In order to apply default F* values, C_u, should be greater than or equal to 6.

b As a result of recent research on construction survivability of geosynthetics and epoxy coated reinforcements, it is recommended that the maximum particle size for these materials be reduced to 19 mm (3/4-inch) for geosynthetics, and epoxy and PVC coated reinforcements unless tests are or have been performed to evaluate the extent of construction damage anticipated for the specific fill material and reinforcement combination.

Corrosion Properties for Steel and Polymers		
Recommended limits of electrochemical properties for backfills when using steel reinforcement		
Property	**Criteria**	**Test Method**
Resistivity	> 3000 ohm-cm	AASHTO T-288-91
pH	> 5 < 10	AASHTO T-289-91
Chlorides	< 100 ppm	AASHTO T-291-91
Sulfates	< 200 ppm	AASHTO T-290-91
Organic Content	1% max.	AASHTO T-267-86

Recommended limits of electrochemical properties for backfills when using geosynthetic reinforcements			
Base Polymer	**Property**	**Criteria**	**Test Method**
Polyester (PET)	pH	> 3 < 9	AASHTO T-289-91
Polyolefin (PP & HDPE)	pH	> 3	AASHTO T-289-91

Figure 12.18 (see color section) shows MSE aggregates backfill material that meets specifications given in Table 12.9. This material was used to build an MSE retaining wall on a NMDOT project in New Mexico. Figures 12.19, 12.20 and 12.21 (see color section) show placement of galvanized steel "grid reinforcement" and erection of precast concrete facing panels on the same MSE wall project in New Mexico.

12.5.2 MSE Wall Design

Mechanically stabilized earth retaining walls are designed in two stages. First, the wall section is designed as a unit, assuming that it will have adequate internal strength to resist external loadings. Second, the wall is designed for internal stresses including interaction of soil reinforcements with MSE fill materials, including reinforcement tensile stresses, pullout performance, reinforcement to wall panel connection strength, and reinforcement size and spacing. Internal MSE wall system performance depends on the type of reinforcing system used such as strips or grids, and it also depends on the reinforcement material type used such as steel or geosynthetics. Since it is not possible to predict which system may be proposed in a contractor's bid, it is standard practice for the contractor to propose a system and provide vendor calculations for review and approval by the project engineers.

Since the overall stability of an MSE wall system is independent of the proprietary reinforcement type selected, the project design engineers perform the overall stability analysis. This initial design stage often is called the global or external stability analysis. The result of this external stability analysis is the size of the minimum required wall section. The analysis steps performed are similar to that required for design of a gravity retaining wall. External stability analysis may include up to six analysis steps: 1. Foundation Bearing Capacity Analysis, 2. Foundation Sliding Analysis, 3. Wall Over-Turning Analysis, 4. Global Wall Stability or Slope Stability Analysis of slip surfaces that pass beneath the wall section, 5. Seismic Stability Analysis, and 6. Wall Settlement

Analysis. A brief discussion of these analysis steps will be included here. For more complete MSE wall analysis details including internal stability analyses, please refer to the Federal Highway Administration report number FHWA-NHI-00-043, "Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines," Elias, V. Christopher, B.R. and Berg, R.R., March 2001.

12.5.2.1 MSE Wall Analysis — General Considerations

The height (H) of an MSE wall is defined as the distance from the top of the wall's leveling pad to the top of the reinforced soil mass or more conveniently to the top of the wall's facing panels. For preliminary sizing, the length of MSE reinforcements is assumed equal to 0.7H, but in no case should reinforcements be less than eight feet (or 2.5 meters) long. If the wall has a sloping surface in front, or if it supports loadings such as an embankment, traffic or structure footings, the required reinforcements will be longer than these minimum values.

For preliminary sizing of reinforcements, MSE fill material is assumed to have a minimum angle of internal friction of 34 degrees and a unit weight of 125 pounds per cubic foot. If the soil material retained behind the MSE wall has been characterized by a geotechnical investigation then those soil shear strength and unit weight parameters should be used in the MSE wall analyses. If the retained soil's properties have not been determined prior to preliminary sizing of MSE reinforcements, it is suggested that the retained soil's internal friction angle be preliminarily assumed to be equal to 30 degrees and its unit weight be assumed to be 120 pounds per cubic foot.

12.5.2.2 MSE Wall Bearing Capacity Analysis

Bearing capacity failure is calculated beneath MSE walls in a similar fashion to spread footings. Two modes of bearing capacity failure were described by Karl Terzaghi (The father of Soil Mechanics) as the general shear failure and the local shear failure. Local shear failure is a "punching in" to soft or loose ground that result in excessive vertical displacement of the wall. General shear failure is when the footing or foundation stresses exceed the shearing strength of the soil causing a rupturing of the foundation support soils. Rupturing of foundation soils by overstressing is called a bearing capacity failure. Assuming that the Meyerhof Bearing Capacity Equation is used, the base of the MSE wall is not buried deeply, the ground surface in front of the wall is level, and there is no ground water, Equation 12-5 gives the ultimate bearing capacity q_{ult}. To use this equation the results of a geotechnical investigation of the MSE wall subsoils must be available to provide the required soil strength and unit weight parameters.

$$q_{ult} = c\ N_c + 0.5\ (L_{soil\ reinforcement})\ (\gamma_{foundation\ soil})\ N_\gamma \qquad (12\text{-}5)$$

where

- c = The soil cohesion or undrained shear strength
- N_c = The cohesion term bearing capacity factor, see Table 12.9
- L = The length of the soil reinforcement which is equal to the width of the wall's "footing"

γ = The unit weight of the subsoil beneath the base of the MSE wall
N_γ = The bearing capacity factor for the gamma term, Table 12.9

The allowable bearing pressure on the bottom of the MSE wall is equal to the ultimate bearing capacity divided by the factor of safety: $q_{allowable} = q_{ult} / FS$, where the FS is equal to 2.5.

If soft, weak cohesive soils exist beneath the base of the MSE wall, a local shear failure could occur. To prevent a local shear failure with its associated lateral spreading, the height (H) of the MSE wall is limited by AASHTO as follows: $(\gamma)(H) \leq (3)(c)$, where γ is the unit weight of the wall backfill material and "c" is the undrained shear strength of the subsoil beneath the wall.

Table 12.9 Bearing Capacity Factors (from FHWA Demo 82, FHWA-SA-96-071)

ϕ, deg.	N_c	N_q	N_γ	ϕ, deg.	N_c	N_q	N_γ
0	5.14	1.00	0.00	26	22.25	11.85	12.54
1	5.38	1.09	0.07	27	23.94	13.20	14.47
2	5.63	1.20	0.15	28	25.80	14.72	16.72
3	5.90	1.31	0.24	29	27.86	16.44	19.34
4	6.19	1.43	0.34	30	30.14	18.40	22.40
5	6.49	1.57	0.45	31	32.67	20.63	25.90
6	6.81	1.72	0.57	32	35.49	23.18	30.22
7	7.16	1.88	0.71	33	38.64	26.09	35.19
8	7.53	2.06	0.86	34	42.16	29.44	41.06
9	7.92	2.25	1.03	35	46.12	33.30	48.03
10	8.35	2.47	1.22	36	50.59	37.75	56.31
11	8.80	2.71	1.44	37	55.63	42.92	66.19
12	9.28	2.97	1.69	38	61.35	48.93	78.03
13	9.81	3.26	1.97	39	37.87	55.96	92.25
14	10.37	3.59	2.29	40	75.31	64.20	109.41
15	10.98	3.94	2.65	41	83.86	73.90	130.22
16	11.63	4.34	3.06	42	93.71	85.38	155.55
17	12.34	4.77	3.53	43	105.11	99.02	186.54
18	13.10	5.26	4.07	44	118.37	115.31	224.64
19	13.93	5.80	4.68	45	133.88	134.88	271.76
20	14.83	6.40	5.39	—	—	—	—
21	15.82	7.07	6.20	—	—	—	—
22	16.88	7.82	7.13	—	—	—	—
23	18.05	8.66	8.20	—	—	—	—
24	19.32	9.60	9.44	—	—	—	—
25	20.72	10.66	10.88	—	—	—	—

12.5.2.3 Lateral Earth Pressure — Sliding and Over-Turning Analyses

Lateral earth pressure on an MSE wall is considered exactly the same as lateral earth pressure on a gravity retaining wall. The Active Earth Pressure Coefficient may be calculated using either the Rankine or the Coulomb Methods. Assuming that the wall has both surcharge and earth pressure loadings, the lateral forces acting on the reinforce soil mass may be calculated by Equation 12-6.

$$F_{Total} = q\ H\ K_a + ½\ (\gamma)\ (H^2)\ (K_a) \qquad (12\text{-}6)$$

where

- F = The total lateral driving force per foot of wall length, pounds
- q = The vertical surcharge loading on the wall, pounds per square foot
- H = The height of the wall, feet
- K_a = The active lateral earth pressure coefficient, unitless
- γ = The unit weight of the retained soil, pounds per cubic foot

To calculate the horizontal resisting force per foot of wall, the total weight of the wall per foot is multiplied by the friction coefficient between the bottom of the MSE wall and the native soil located beneath the wall. Assuming that the internal friction angle, ϕ of the native soil beneath the wall is less than the internal friction angle of the MSE wall backfill (i.e., which is assumed to be 34 degrees), the friction coefficient between the base of the MSE backfill and the native soil is given as $f = \tan \phi$. Then the resisting shearing force per foot of wall length is equal to the weight of wall per foot of wall length times the friction factor, f.

To check the sliding stability of the MSE wall, the factor of safety with respect to sliding along the base of the MSE wall should be greater than or equal to 1.5 as illustrated in Equation 12-7.

$$FS_{Sliding} = \frac{(\sum \text{horizontal resisting forces})}{(\sum \text{horizontal driving forces})} \geq 1.5 \qquad (12\text{-}7)$$

To check the overturning stability of an MSE wall, or any gravity retaining wall, the engineer must calculate the overturning moments generated by all of the lateral forces acting on the wall and compare them to the resisting moment which is generated by the weight of the wall. Normally the resisting moment due to the wall's self-weight is divided by the overturning moments acting on the wall and a factor of safety is calculated. This calculated moment is normally compared to an allowable factor of safety of 1.5. If ground water seepage or wet clay fill is behind the MSE wall the required factor of safety is often increased to 2.0 or more.

The remaining MSE wall stability analyses are the Global Wall Stability, the Seismic Stability Analysis and Settlement Analysis. To perform the global wall stability analysis, a geotechnical engineer is required to perform a slope stability analysis of the wall section and the surrounding soil above, behind and below the wall. This analysis requires knowledge of the wall and surrounding soils' loading history before, during and after construction of the wall. This analysis also requires identifying soil layers present at the site with both drained and undrained shear strength data for each layer. To perform these slope stability analyses requires advanced soil mechanics theory and use of a slope stability computer program. Detailed discussion of soil stability analysis is beyond the scope of this presentation. Seismic Stability analyses often are included in the slope stability computer analysis of the MSE wall section by adding factors equal to the horizontal and vertical seismic loading component. These seismic factors, which are given in building codes, are expressed as acceleration equal to a percentage of gravity.

Settlement of MSE walls is estimated by use of standard geotechnical methods for determining immediate, consolidation and secondary compression settlements. Please refer to a standard geotechnical text for details of these calculation procedures.

12.5.2.4 Spread Footings Supported on an MSE Wall or Reinforced Earth

Many bridges in the United States are supported on spread footings supported on the reinforced earth section of an MSE retaining wall. The vertical loading from the bridge footing has to be included in all of the MSE wall analyses. Since ordinary bearing capacity analyses do not directly apply to a reinforced soil section, the bearing capacity of the bridge footing is often selected as 4000 pounds per square foot (190 kN/m^2). If the presumed bearing pressure results in a reasonably sized footing, the footing is designed for this bearing value and the MSE wall is designed for this surcharge pressure.

Because MSE supported bridge abutment footings will likely settle more than pile supported center piers, many State Departments of Transportation use MSE supported spread footings on single span bridges only. Analyses can be done to compare settlements of pile-supported piers with MSE supported abutments. Guidance for acceptable differential settlements of multiple support bridges is included in the Federal Highway Administration Publication No. FHWA-NHI-00-043, "Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, Design and Construction Guidelines," March 2001.

12.6 Water and Wastewater Treatment

12.6.1 General Considerations

Aggregates used in the treatment of water and wastewater (sewage) can be classified in terms of (1) the function performed, and (2) the manner in which it is performed.

All the commonly used methods of water and wastewater treatment utilize a filter in the process. Not all of these methods, however, count on the actual filtering function of aggregates to achieve the desired treatment. For water purification, aggregates for the most part are used as a true filter, as the term is used in this chapter. In biological trickling filters used for wastewater treatment, the filtration function does not actually take place. Instead, the filter simply provides the medium on which the wastewater is broken down and purified by biological processes.

Filter Types: In water treatment the filtration process is usually performed through the use of a slow sand filter or a rapid sand filter (see American Waterworks Association, Inc for slow and rapid sand filter design manuals). *Slow sand filters* are characterized by slow filtration rates, using relatively fine sand. They require relatively infrequent cleaning. *Rapid sand filters* use much coarser filter media and operate at much higher filtration rates. Rapid sand filters require frequent cleaning. To have equal cleansing potential, the slow sand filter must have a much larger surface area in contact with the raw water than the rapid sand filter.

The two most common processes that utilize aggregates in the primary treatment of wastewater are (1) trickling filters and (2) intermittent sand filters. *Trickling filters* generally consist of coarse aggregates over which sewage is applied slowly in the form of spray or drops. The purpose of the aggregates is simply to support colonies of organisms, which exist in microbial layers on the surface of the aggregates and feed on the organic matter in the wastewater in an aerobic environment. An *intermittent sand filter* generally consists of fine, sand-sized aggregates to which a predetermined quantity of wastewater is intermittently applied. The percolation process is much slower than in trickling filters, and the filter performs both a true filtration function and biological treatment.

The purification techniques described above all employ aggregates and are usually only one part of the treatment process. The design of these treatment systems depends upon the degree of pretreatment that the water or wastewater receives before being exposed either to filtration or biological contact and the required final degree of purification. Only aspects of design directly related to the aggregates used in these systems are considered here.

12.6.2 Water Treatment

12.6.2.1 Slow Sand Filters

Slow sand filters are no longer popular in treatment plants for medium to large cities in the United States primarily because of the high cost of constructing the required large filter beds. Slow sand filters are still used in small towns and in remote areas of the United States and in developing countries.

Essential Parts: The essential parts of a slow sand filter include (1) a supernatant water reservoir, (2) a filter bed, (3) a filter bottom and under-drainage system, (4) a filter box containing these elements and (5) a filter control system. The number and area of the filter boxes depends on the volume of water to be treated on a daily basis.

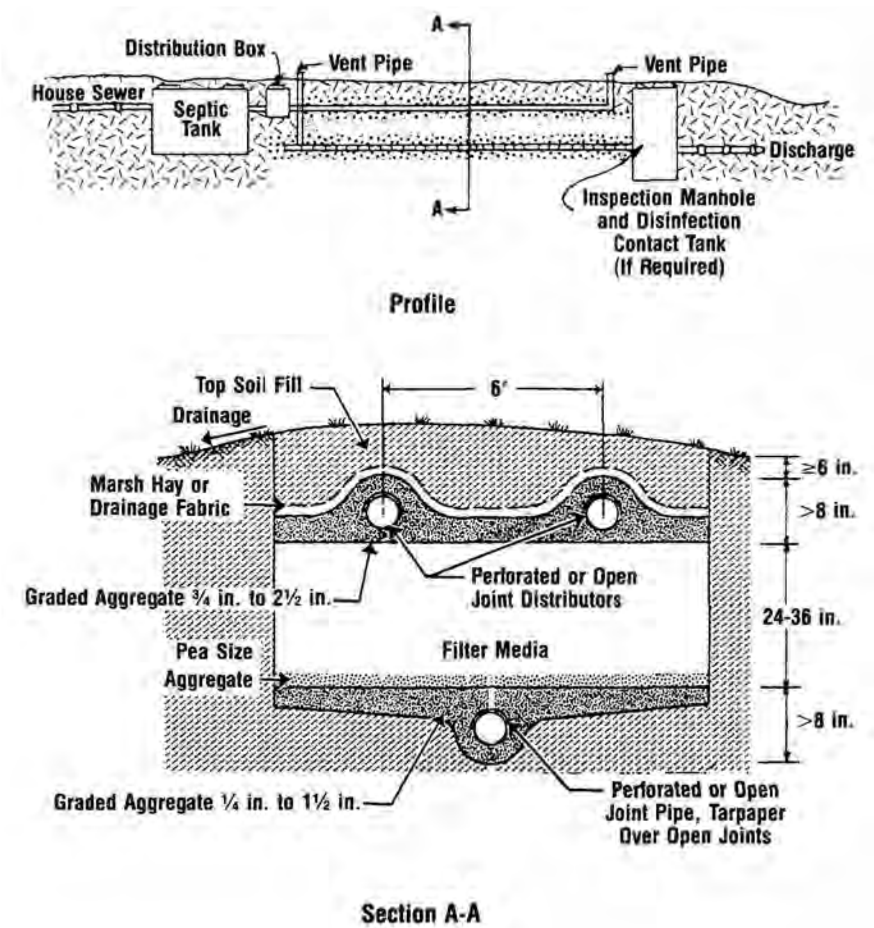

Figure 12.22 Typical buried intermittent filter installation.[39]

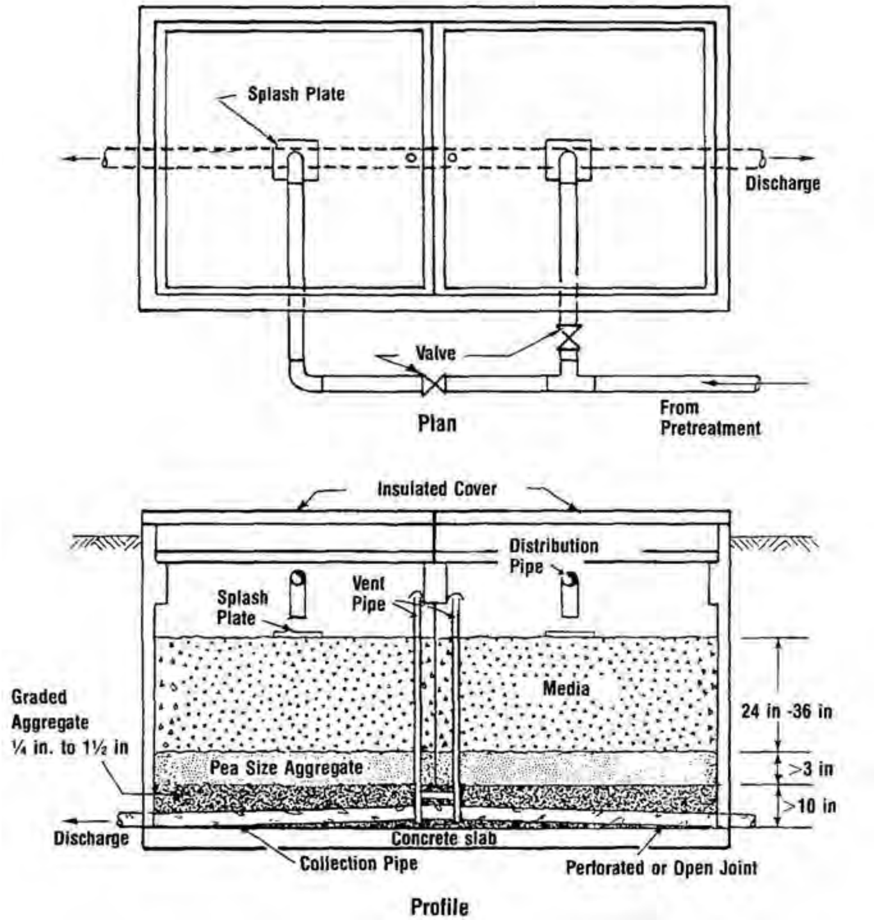

Figure 12.23 Typical Free Access Intermittent Filter.[39]

12.7 Erosion Control and Scour Protection — Riprap and Gabions

12.7.1 Introduction to Riprap Design

Riprap is a natural rock that consists of larger aggregates, such as stones or boulders, which has been compacted or placed along engineering structures to provide protection against erosion and scour. It has been used to remedy a variety of civil engineering problems regarding erosion and scour along streams and riverbanks, bridge piers and abutments, and at the toe and on the side slopes of landfills to prevent erosion and scour. Riprap protection and scour protection go hand in hand. Scour is defined as a natural or man-made disturbance caused by turbulent and powerful erosional forces, which could endanger the stability of a structure. Riprap is a countermeasure used to reduce or prevent the effects of scour on those structures. This section will discuss the relation and difference between riprap protection and scour protection, and how the solution of riprap and scour protection have been used to reduce and possibly eliminate the chances of instability to a structure affected by hydraulic stresses.

In riprap design, the primary controlling factors to a functional revetment riprap (that is rock facing on an embankment) depends on the source and competence of the rock used. Typical rocks to avoid include weathered or altered rocks, rocks containing soluble or expansive minerals, vesicular basalt, shale, claystone, siltstone, weakly cemented or porous sandstone, schist or phyllite. For revetment riprap, the methods and equipment to collect, transport and place the riprap are also key factors to consider in design and construction. The rock must meet design specifications based on size, shape, density, gradation and durability. In some cases, filters layers may be required to bed the riprap and to provide filtering protection to retain the subgrade soil particles beneath riprap. A filter-bedding layer is not required for all riprap designs; however, it provides a free flow pathway for water to permeate through the interface between the riprap layer and the underlying subgrade soil, thus increasing the overall performance of the riprap design. Common types of riprap bedding filters include geotextiles and/or aggregates underlayers composed of coarse sand and gravel. In special cases, both geotextiles and aggregates underlayers may be required to increase the overall performance of the riprap design.

12.7.2 Riprap Specifications

Aggregates used for riprap design must meet specific requirements. According to the National Cooperative Highway Research Program (NCHRP), specifications for classifying riprap size and gradation varies among each state. Throughout the years, there have been several techniques used to determine the size and extent of a riprap installation. Most designs for riprap installations are based on experience in the field and the results of laboratory tests. Presently, there are no definitive classifications or specifications for riprap designs; however, several different methods have been created to determine sizing, layer thickness and gradation of rock riprap. These methods can be obtained from the U.S. Army Corps of Engineers (Engineer Manual 1110-2-1601); the Federal Highway Administration (Hydraulic Engineering Circular No. 11); U.S. Bureau of Reclamation (Engineering Monograph No. 25); U.S. Geological Survey (Water Resources Investigation Report 86-4127); the California Bank and Shore Protection Manual; the Isbash (from USACE Engineer Manual 1110-2-1601 and the National Cooperative Highway Research Program Report 568); and the American Society of Civil Engineering (Manual 54). Basic specifications for all methods of riprap design include the requirements that aggregates must sustain durability, gradation, shape and ratio of sizes according to the design of the riprap. It is very important that rocks used in riprap design have an allowable range of shapes, sizes and density to provide for an effective design and an economic installation of a suitably protective riprap layer.

As stated earlier, several equations have been derived to determine sizing, layer thickness and gradation of the riprap rocks. The Isbash method, for example, is a method that could be used to estimate stone size or the average velocity of water flow against given aggregates that will remain stable. Equation 12-8 is one of the most popular equations by Isbash to determine the mean flow velocity against the aggregates:

$$V = C[2g(S - 1)]^{½}(d_{50})^{½} \qquad (12\text{-}8)$$

where

- V = Mean Velocity against aggregates, ft/s or m/s
- C = Isbash constant (0.86 or 1.20) (see determination below by Lagasse, 2006)
- g = Acceleration of gravity, ft/s2 or m/s2
- S = Specific gravity of stone
- d_{50} = Median diameter of spherical stone, ft or m

According to the NCHRP Report 568, the lower value for the Isbash constant represents the flow velocity at which loose surface stones first begin to roll. The higher value represents the flow velocity at which stones protected by adjacent particles begin to move and roll until they find another "seat" (Lagasse, 2006).

Despite the fairly simple steps used to calculate the mean flow velocity, the Isbash equation was further modified to estimate the required aggregates size for a horizontal bed. The equation below is a modified version of Isbash equation:

$$d \geq 0.7 \frac{V^2}{2g\Delta}\left(1 - \frac{\sin^2\theta}{\sin^2\phi}\right)^{-½} \qquad (12\text{-}9)$$

where

- V = Current velocity
- Δ = Specific weight of the submerged stone, $\Delta = (SG-1) = (\gamma_s/\gamma_w - 1)$
- θ = Bank slope
- ϕ = The internal friction angle taken to be about 40° for aggregates riprap

The size of aggregates used in riprap design is expressed in terms of its diameter or weight. The design of riprap and the size of aggregates used vary based on the intensity of the hydrodynamic forces present in the environment for which it is used. Designed riprap aggregates are specifically sized and selected to prevent failure from erosion, mainly particle erosion or movement. The design requirements for sizing of aggregates usually is expressed in terms of stones size D_n, where "n" represents the percentage of the total weight of the graded material that contains aggregates of less weight. An equation that relates between the weight and size of the aggregates has been formulated based on the spherical shape as:

$$D_n = \left(\frac{6W_n}{\pi \gamma_s} \right)^{1/3} \tag{12-10}$$

where

D_n = Equivalent-volume spherical aggregates diameter, ft
W = Weight of individual aggregates having a diameter of D_n
γ_s = Saturated surface dry specific or unit weight of aggregates, pounds per cubic foot

The shape of aggregates is equally important in riprap design. Shapes of aggregates should be angular, preferably blocky with clean edges at the intersections cut in flat faces. The angularity of aggregates provides a stronger interlocking advantage between each stone as opposed to sub-angular or rounded aggregates, which have smoother surfaces that tend to have lower amounts of friction between each stone. Aggregates with sharp, angular, clean edges at the intersections tend to have more resistance to movement and are less likely to be moved or eroded by channel flow.

The gradation of aggregates in a riprap revetment should be "well-graded" throughout the riprap layer thickness. The gradation is a major contributor to the design, especially in light of the fact that gradation helps the riprap from eroding. It should be "well-graded" from the smallest to the maximum size recommended for the design. In many riprap designs, sizes of aggregates specified ranges from D_{30}, the minimum specified size, to D_{100}, the maximum specified size for aggregates. According to the Federal Highway Administration specification for the Design of Riprap, riprap used should provide for two limiting gradation curves, See Table 12.10 and the stone gradation (as determined from a field test sample) should lie within these limits. Suggested gradation classes based on AASHTO specifications are presented in Table 12.11, which have been provided by the Federal Highway Administration, Design of Riprap Revetment, 1989.

Table 12.10 Rock Riprap Gradation Limits

Stone Size Range (ft)	Stone Weight Range (lb)	Percent of Gradation Smaller Than
1.5 D50 to 1.7 D50	3.0 W50 to 5.0 W50	100
1.2 D50 to 1.4 D50	2.0 W50 to 2.75 W50	85
1.0 D50 to 1.15 D50	1.0 W50 to 1.5 W50	50
0.4 D50 to 0.6 D50	0.1 W50 to 0.2 W50	15

Table 12.11

Riprap Class	Rock Size[1] (ft)	Rock Size[2] (lbs)	Percent of Riprap Smaller Than
Facing	1.30 0.95 0.40	200 75 5	100 50 10
Light	1.80 1.30 0.40	500 200 5	100 50 10
¼ ton	2.25 1.80 0.95	1000 500 75	100 50 10
½ ton	2.85 2.25 1.80	2000 1000 500	100 50 10
1 ton	3.60 2.85 2.25	4000 2000 1000	100 50 10
2 ton	4.50 3.60 2.85	8000 4000 2000	100 50 10

1. *Assuming a specific gravity of 2.65*
2. *Based on AASHTO Gradations*

In addition to shape and size, the aggregates must maintain a specified allowable density of 150 to 175 pounds per cubic foot (pcf). Due to the fact that riprap sizing is sensitive to unit weight of the aggregates, the unit weight of the stone should be determined to the nearest pound per cubic foot value. Aggregates obtained from the same geologic formation in the quarry will have approximately the same unit weight whereas aggregates obtained from a selected number of quarries will have significant differences in unit weight due to variations in rock mineralogy.

Durability is another essential characteristic important for the life cycle of riprap. The degree of durability for rocks used in riprap design depends on the quarry from which it has been excavated and processed. If a quarry operator "over blasts," the resulting riprap rock pieces may be excessively fractured and cracked. Generally, rocks that possess consistent shape, size, and gradation have the tendency to resist erosion and withstand weathering, which includes freezing and thawing ranges. The durability depends on the rock's mineralogy, porosity, weathering, discontinuities and conditions at the site. Suitability of rocks used for riprap design are normally tested in the laboratory, but also may be determined by observation and dye testing of the surface of the rock in its natural state and in the quarry after blasting. Rocks with visible indications of weathering or fracturing that easily break down physically or chemically are not ideal candidates when used in actual riprap design, neither are rocks that have been altered including soluble rocks or expansive minerals. Typical rocks to avoid when considering riprap include shale, claystone, siltstone, vesicular basalts, cemented or weakly cemented sandstone, schist and phyllite.

12.7.3 Types of Riprap Revetment

Three techniques are used to place aggregates for riprap revetments including dumped riprap, hand-placed riprap and plated riprap.

Dumped riprap is a technique where graded aggregates are dumped on a slope by mechanized methods such as crane and skip, dragline or some form of bucket. As the aggregates are dumped, individual pieces independently adjust and interlock by means of gravity. When riprap is installed by this method, segregation of the aggregates is avoided by a careful equipment operator and is checked by the on-site construction inspector. This method allows for flexibility in the riprap blanket. Construction of dumped riprap is simple and economical. When blanket damage occurs, placing more riprap over the damaged area easily repairs the riprap blanket.

The second technique is achieved by hand-placing the aggregates on a slope. This method involves carefully placing aggregates by hand to reduce voids between the smaller and larger aggregates. Even though this method is labor-intensive and expensive, hand-placed riprap provides an aesthetic appearance to the riprap placed and reduces the flow turbulence at the water-revetment interface. In cases where hand-placed riprap designs are applied, the layer thickness can be reduced by 6 to 12 inches less than an equivalent loose dumped riprap design. In addition, the hand placement technique allows designs for riprap slopes to be steeper due to the tight interlocking of individual aggregates as compared to looser aggregates in a dumped riprap installation. Although hand-placed riprap provides excellent interlocking between aggregates, the probability for slope failure is higher with this method. This is due to the fact that when the riprap design is hand-placed, it is less flexible and small shifts or minor movements in the aggregates base layer may cause failure to the revetment layer.

Plated riprap is similar to hand-placed riprap in appearance and behavior, but methods of placing plated riprap are different. An installation of plated riprap is achieved by placing rock on a bank of a slope and tamping it into place by use of a steel plate. This provides additional stability of placement for the aggregates. Tamping also fractures and breaks the larger rocks into smaller aggregates to help fill voids in the riprap layer. Some advantages to this placement technique include the use of steeper slopes in riprap design and reduction of the required riprap layer thickness by 6 to 12 inches less than a dumped riprap installation. Failure of a plated riprap installation can occur if one or more of the aggregates at the base of the slope become displaced or removed. In addition, flexibility of plated riprap is lower than dumped riprap as described for hand-placed riprap above.

12.7.4 Riprap Design Failures

All engineered designs are susceptible to potential failures and revetment riprap is among the many engineering techniques that have undergone failure. There are four types of failure for revetment riprap that include particle erosion, transitional slide, modified slump failure and slump failure. The causes for failure are a result of a number of inadequacies in the design from gradation of the stones, steepened angles of the slopes of the design, to a constant presence of excess hydrostatic pressure, and poor foundation support at the toe of the riprap blanket or by shear failure of the underlying base material that supports the riprap.

One common type of riprap failure is particle erosion. It occurs when individual pieces of riprap are removed by the forces of flowing water. This occurs when stone sizes are not large enough to resist hydraulic forces or individual stones have been removed by debris impact. Based on field observations, the causes of particle erosion include aggregates sizes are not large enough to sustain stability; individual aggregates have been removed by debris impact or abrasion of constant or sporadic hydraulic forces; the side of the slope of the revetment is too steep to maintain stability such that the angle of repose has been exceeded; and/or the sizes of the riprap pieces are too uniform to provide adequate interlocking. Particle erosion is normally initiated by abrasion of flowing water, eddy action and reverse flow, local flow acceleration, freeze and/or thaw action, and ice or toe erosion.

Transitional slides are caused by the down slope movement of a mass of stones in the upper portion of the riprap bank that extends parallel to the channel alignment. This type of failure is normally associated with scouring of the channel bed, which could weaken the toe of the riprap blanket causing a movement along the horizontal plane of the blanket. A translational failure starts when cracks appear in the upper portion of the riprap bank. These cracks can extend parallel to the channel along the riprap. As the slide advances due to gravity and the weight of the aggregates, the lower portion of the riprap separates from the upper half and causes a sliding effect of all the materials of the lower portion down toward the toe of the riprap. As a result, the failure has a bulge at the toe of the riprap. In most translational slides, the initial causes are due to particle erosion of the toe material or any other mechanism that causes instability at the toe of the riprap. The causes of translational failure are often due to the presence of excess hydrostatic pressure in the riprap, the lack of stability at the toe of the riprap which causes a chain reaction for failure in the upper portion of the riprap, and the steepness of the bank sides of the slopes are too high.

The third type of failure is the slump failure. The slump failure is described as a rotational-gravitational movement of material along the surface of the rupture that has a concave upward curve (Lagasse, 2006). Slump failures are caused by shear failure of the underlying base material that supports the riprap when subjected to excess pore pressure. Most slump failures are caused by an overburden of the top of the slope of the riprap or the steepened side slopes of the bank creating a greater gravitational force to the inertia forces of the riprap and base material along the friction plane or the sides of the slope bank are too steep to create a larger gravitational force than the inertia forces in the riprap.

The fourth type of failure is the modified slump failure. Similar to a translational slide failure, the modified slump failure is a mass movement of material along an internal slip surface in the riprap blanket. The only difference is the geometry of these slide failures. The translational slide failure occurs along a horizontal plane, whereas a modified slump failure occurs in an irregular form in the riprap at the place of failure. In a modified slump failure, the underlying material, which supports the riprap, does not experience failure. Typical causes of the modified slump failure include a steepened slope bank of the riprap where the angle of repose and the angle of the bank slope are too close which causes an imbalance or movement in individual aggregates to create instability for other aggregates in the blanket; and the material used to support the upslope of the riprap is dislodged by settlement of the submerged riprap, impact, abrasion, particle erosion, or some other cause.

12.7.5 Riprap Bedding, Aggregates Filters and Geotextiles

12.7.5.1 Use of Bedding, Aggregates Underlayers Geotextiles

Aggregates underlayers and geotextiles are used as additional protective layers to help control water and relieve the amount of hydrostatic pressure on a structure. In special cases, geotextiles have been used with aggregates underlayers to increase the overall performance in pavements, retaining walls, earthen embankments, drain construction, concrete revetment, riprap and other structures. If used, aggregates underlayers and geotextiles can provide a suitable filtration process and a free flow pathway for water through the interface between the structure and the underlying soil.

Aggregates underlayers and geotextiles are used mainly on non-cohesive soils that are prone to extreme subsurface drainage such as areas with shallow groundwater depths. It is dependent on the subsurface conditions, the hydraulic analysis and the type of construction. When aggregates underlayers and geotextiles are used in riprap design, it helps to prevent the migration of finer subgrade soils through voids in the riprap layer. Aggregates underlayers and geotextiles are usually placed beneath the structure and above the underlying subgrade soil.

12.7.5.2 Use of Geotextiles

In many engineering structures such as MSE retaining walls, earth embankments, pavements, railroads, concrete revetment, drain construction and riprap, geotextiles may be included in the design if their design life is compatible with the overall system's design life. The use of geotextiles helps to increase the stability of the soil underlying the structure by providing proper drainage of excess water, filtration, separation between layers, reinforcement to the structure and control of sediments and erosion or if used with asphalt may be used as an moisture barrier. Geotextiles are not composed of aggregates, but are used in conjunction with aggregates like riprap or aggregates underlayering. Their purpose is as important in riprap as an aggregates underlayer which is to retain base material and prevent pore pressure buildup.

Most geotextiles are composed of polypropylene, polyester, polyethylene, polyamide, polyvinylidene chloride and fiberglass, and are constructed by a weaving/knitting process or a non-weaving/knitting process that involves bonding by needle punching, heat bonding, resin bonding or a combination of each bonding process. Construction by bonding usually results in a thicker, but lighter geotextile than a woven geotextile. Non-woven geotextiles are normally lighter in unit weight as compared to a woven geotextile and range between 100 to 1,000 g/m^2; whereas woven geotextiles weigh up to 2,000 g/m^2. Woven geotextiles are manufactured as flat sheets of two sets of threads typically made of mono-film fabrics, multi-filament fabrics or tape fabrics.

An advantage of geotextiles includes quick and easy installation. In addition, geotextiles are often economical in terms of materials, labor and equipment used. Beyond these advantages, geotextiles have exceptional tensile strength. Installation of geotextiles underwater is difficult. Geotextiles have sensitivity to the surrounding conditions, i.e., pH of water, bacterial activity hydraulic activity. These limitations should be considered when selecting the type of geotextile to be used.

As with all engineering designs, geotextiles must maintain a specified degree of durability to function appropriately for its design purpose. Most geotextiles are reported to last approximately 30 years depending on the conditions of the site. Geotextiles can be useful when providing reinforcement to aggregates and earthen structures; however, exposure to sunlight can degrade the physical properties of the polymers. In some cases, extremely high temperatures melt the polymers especially when used with asphalt. In contrast to high temperatures, extremely cold temperatures can make the polymer brittle and difficult to handle during installation. Another important factor to consider when installing geotextiles is the environmental conditions and the presence of water. Water is a powerful agent and geotextiles can be sensitive if the pH level is too high or too low. Too high of a pH level affects polyester and too low of a pH level affects the polyamides, therefore, it is imperative all factors be considered in selecting the appropriate geotextile material.

12.7.5.3 Use of Aggregates Underlayers

Aggregates underlayers also are known as granular filters, aggregates filters and/or granular underlining. Most aggregates underlayers are composed of gravel and/or medium-grained size sand and can be used alone or with geotextiles. These aggregates components should be dense, hard, and durable to withstand constant and irregular flow velocities. The particle size distribution curve is a practical indication of the appropriate gradations of filters to be used with on-site subgrade soils. Several publications provide recommendations and determinations of permeability in reference to the particle-size distribution curve. For example, the Design of Riprap Revetment by the Federal Highway Administration recommends that the filter material have a grading defined as the ratio of the 15 percent particle size (D_{15}) of the coarser layer to the 85 percent particle size (D_{85}) of the finer layer. According to Lagasse, the gradation curve for granular filter material should be approximately parallel to that of the base soil. In the National Cooperative Highway Research Program for Riprap Design Criteria, a procedure developed by Cistin and Ziems presents criteria that the d_{50} size of the filter is selected based on the coefficients of uniformity (D_{60}/D_{10}) of both the base soil and filter material. This means the gradation curve of the granular filter material should be approximately parallel to that of the base soil (Lagasse, 2006). Figure 12.26 provides a filter design chart according to Cistin-Ziems procedure, which is used to determine the key indices for base soil.

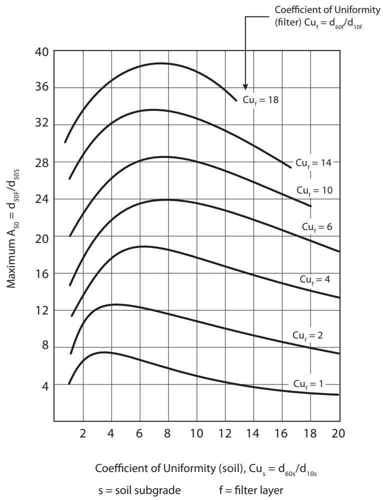

Figure 12.26 Cistin-Ziems Filter Design Chart

Aggregates underlayers have a thickness of 6 to 15 inches for a single layer. A typical minimum thickness for aggregates underlayers should be 6 to 8 inches and no less than 6 inches for a single layer. Other designs composed of multiple layers require 4 to 8 inches for individual layers according to study by Brown and Clyde in 1989. Should an aggregates underlayer be placed underwater, recommendations are to increase the thickness by 50 percent.

Similar to geotextiles, aggregates underlayers provide drainage of excess water, filtration, erosion control and sediment control, and additional reinforcing stability to the design. As a result, aggregates underlayers prevent the downslope migration of bank material if subjected to wave action.

12.7.6 Gabions – Riprap in Protective Baskets

Gabions are wire mesh baskets filled with aggregates of variable sizes. This engineering technique is considered the most economical and flexible alternative to riprap. It is an application used to improve the stability of retaining walls, revetments, and other structures affected by the erosive forces of water. Gabions are very similar to riprap in a sense that both techniques use large aggregates to decrease the erosion and sediments along riverbanks, streams, and shores. The use of gabions to prevent erosion is not a modern concept. In fact, gabions were applied to the banks of the Nile River in ancient Egypt more than 2,000 years ago. The Egyptians used cylindrical willow baskets filled with small stones to protect the over-flooding riverbanks of the Nile. In the late 19th century, willow lined baskets were replaced by metal wire netting or baskets similar to those used today.

The word gabion originates from an Italian word "Gabbione" meaning "Big cage." Today, gabions have improved significantly. According to the article 'Gabions for Streambank Erosion Control," gabions come in three different forms: the gabion basket, the gabion mattress; and the sack gabion. All forms consist of a wire mesh container filled with aggregates materials. The only difference is the gabion shape and its application location. Gabion baskets are usually 18 to 36 inches in thickness when applied to the retaining of slopes of the banks of rivers and streams. The thickness of gabion mattresses normally range from 6 to 18 inches and is used to protect the bed or bank surface of the slopes from erosion. Gabion sacks are bags of aggregates materials that do not have a specific form, but can still be used to prevent erosion.

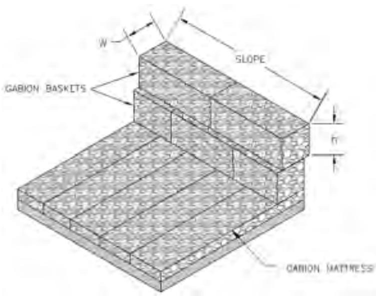

Figure 12.27 Illustration of gabion basket to create retaining wall courtesy of Terra Aqua Inc, a manufacturer and contractor specializing in design, specification and construction of gabion systems.

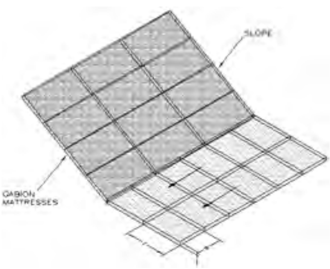

Figure 12.29 Illustration of gabion mattress lining installation by Terra Aqua, Inc. along slope of riverbank

Gabions have several advantages to the structure and for the environment. When used properly, gabions have the ability to drain water freely and decrease the hydrostatic pressure acting on the structure. This advantage prevents damage to the structure caused by the constant thawing and freezing of water, which can lead to the chemical and physical breakdown of the aggregates materials and corrosion of the wire mesh baskets. Over time, a properly installed gabion can collect soil within the aggregates materials to sustain vegetation, which helps to increase stability, resist erosion and improve the "natural" appearance of the structure. In addition, use of gabions benefits the environment by providing an aesthetic appearance to the structure and ecological improvement to the surroundings.

Another gabion advantage is flexibility. Gabions can be constructed to any form, whether it is cylindrical, cubic and/or rectangular. Since the mesh confines the aggregates materials, the potential for aggregates to become loose and wash away is small as opposed to the unsecured, loosely placed riprap material. Gabions also have the ability to adjust to the conditions of the site while it maintains its function by conforming to the ground surface. Although riprap is preferred and highly recommended as a solution to many applications, the suitability of applying riprap may not be appropriate to its use in several circumstances. For one thing, riprap requires a specific amount and size of material to be used. In some cases, large aggregates needed for riprap are not available. Available sizes of the aggregates may be too small to use on large streams or on riverbanks or not available in the area, therefore leading to the requirement of transportation of aggregates from remote sites, which increases project costs. When gabions are applied, lesser sizes and amounts of aggregates are utilized and the aggregates used do not have to have strict grading requirements compared to riprap.

Gabions do have disadvantages. Construction of gabions can be expensive due to the amount of labor involved in their construction. Regionally, these construction costs are dependent on the costs of available manual labor at the time of installation. Currently, the average cost of construction of gabions is reported at ranges from $175 to $200 per cubic yard for installation, materials and labor with use of construction equipment.

Gabions have the potential for failure depending on the site conditions. At sites where gabions are placed underwater, the wire mesh baskets that contain the aggregates materials have the tendency to corrode and eventually break under loading. These breaks could form large openings in the wire mesh baskets and release or loosen the rock fill material, which could ultimately lead to instability. Due to the extensive use of gabions during the past 30 years, procedures to lessen deterioration of the wire mesh baskets have been devised by coating the wire with plastics such as polyvinyl chloride (PVC). Despite the preventive measure taken, wire mesh baskets continue to undergo corrosion when water is present. Other disadvantages of gabion use include instability when the mesh wire baskets are intentionally cut due to vandalism or additional surcharge loading is applied at the top of these structures.

12.7.7 Gabion Design

Gabions are an effective and efficient solution to erosion control. When properly installed and appropriately maintained, a gabion design can last well over its predicted life cycle. Several specifications apply to gabion designs. The fill material used in gabion designs must be clean and durable to withstand weathering and erosion. Aggregates should be evenly graded and sustain enough angularity to provide adequate interlocking contact with one another. Aggregates used should have a specific gravity of 2.4, but it can be lower if tests are conducted to confirm the gabion's stability. Size for filling material is based on a design that depends on the distance between the twists of the gabion's wire mesh. Ultimately, aggregates with diameters larger than the distances between the wire-mesh twists are preferred. Minimal distances between the twist is 80 millimeters (approximately 3 inches) for gabions.

Specifications for the use of gabion mattresses are based on a shear-stress or critical velocity approach. In recent studies of gabion-mattresses, calculations to determine the average filling rock diameter have been expressed using the following equation:

$$\frac{d_m}{h} = C_s \left[\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{0.5} \frac{V_s}{\sqrt{gh}} \right]^{2.5} \qquad (12\text{-}11)$$

where

d_m = The average filling rock diameter in the mattress (m)
h = Design depth of water over top of mattress (m)
V_s = Depth-averaged velocity (m/s)
γ_w = Unit weight of water (kg/m^3)
γ_s = Unit weight of the stone (kg/m^3)
g = Acceleration due to gravity (m/s^2)
C_s = Stability coefficient of the particles (empirically estimated as 0.1)

The value of C_s was calculated by Maynord (1995). Maynord based the calculation on a model data from Simons et al (1984) that experimentally established the flow conditions under which rocks begin to move in a gabion mattress.

During the construction phase, the wire mesh baskets for gabions are simple to assemble. The ends of the wire mesh are jointed at the edges and laced together vertically and horizontally. This provides structural strength and integrity. Once the wire mesh baskets are assembled, aggregates can be filled into the basket. It is important to achieve minimal void spaces between each aggregates particle by packing the baskets or mattresses tightly. Improper aggregates placement and compacting into the baskets may result in distortion and flexing which can lead to wire fatigue and eventual failure.

To avoid inconsistencies with the design and construction of gabions, it is good practice to perform frequent inspections during construction, and periodic inspections and maintenance during their operational life. This inspection procedure will likely prolong the life cycle of gabion structures.

12.8 Rammed Aggregates Piers and Stone Columns

12.8.1 Introduction for Rammed Aggregates Piers

Rammed Aggregates Piers (RAP) also known as Geopier® elements, (the name 'Geopier' is a U.S. patent trademark of the Geopier Foundation Company, Incorporation) has become an alternate method to reinforce poor to fair foundation soils. Some of those soils include soft to medium stiff clays, loose to medium dense sands and silts, organic silts, peat, and uncontrolled, uncompacted fills. Since 1984, the use of RAP elements has become more popular and practicable in foundation engineering applications. Use of Rammed Aggregates Piers has been developed as an alternative to driving piles, installing drilled piers, or to removing unsuitable, soft, compressible soils and replacing them with engineered fill. By 1988, RAP elements were being used on various projects for single story structures to sixteen story structures as well as storage silos and airplane hangars (Lawton, 1994).

RAP elements are versatile, economical, and use unreinforced, compacted aggregates as the main element in foundation soil improvement. This method of using aggregates in foundation improvement provides an engineering solution to control excessive foundation settlement as well as uplift and horizontal movement control for shallow and deep foundations, steel storage tanks, retaining wall foundations and for support of highway embankments. High angles of internal friction are achieved in the RAP aggregates shafts by use of ramming or vibratory compaction with a vibratory pile hammer during aggregates filling of shaft holes. The resulting strength of RAP elements can be used to reinforce a slope by increasing the factor of safety against slope instability. The use of RAP elements increases strength and stiffness by increasing the density of the soil surrounding the compacted aggregates shafts. In addition, RAP elements allow lateral prestressing of the surrounding soil and provide a drainage path for dissipation of pore water.

12.8.2 Field and Laboratory Tests

Field and laboratory tests have been performed to determine engineering properties of RAP elements. Full-scale direct shear tests were performed at the top of a 30-inch diameter Geopier element and small-scale laboratory triaxial tests were performed on reconstituted samples to determine the shear strength of Geopiers (Wissmann, 2002). These tests have indicated an impressive peak angle of internal friction ranging from 49 degrees from open-graded stones (no fines) to 52 degrees for well-graded stones (5 to 10 percent non-plastic fines) as compared to matrix soils with low or no angle of internal friction. Results reported from laboratory triaxial tests have indicated a peak friction angle of 51 degrees for piers constructed from well-graded stone (Wissmann, 2002).

It is currently common practice to perform full-scale load tests on every RAP project to confirm the load capacity of the RAP elements. These tests include an installed test element, uplift elements, and a telltale that consists of a steel plate attached to sleeved threaded bars. The telltale is installed at the bottom of the element during construction. During the test (see Figure 12.32, color section) a hydraulic jack applies downward loads and deflections are measured at the top of the element and for the telltale at the bottom of the element (Wissmann, 2002).

12.8.3 Construction of Rammed Aggregates Pier Elements

RAP elements usually are constructed by drilling 24- to 36-inch holes to depths ranging between 7 to 30 feet. See Figures 12.8.3.2 and 12.8.3.3. The hole's depth is dependent on the design load recommendations and will vary according to site-specific subsurface soils. In some cases, RAP elements have been installed to depths between 1 to 2 times the width of the foundation footing for settlement control and are also equipped with uplift anchors to prevent overturning moments caused by uplift forces generated by strong winds or earthquakes. Once the drilled hole has been excavated, clean aggregates material is placed in the bottom of the excavated shaft. The aggregates material is then rammed with a static or dynamic hammer. The Geopier Company uses a patented 27-inch beveled tamper driven by a modified 3,000 to 4,000 pounds hydraulic hammer shown in Figure 12.33, color section. Geopier's patented tamper delivers 300 to 400 blows per minute or 1 to 2 million feet per pounds of compacting energy per minute. This initial ramming or compacting process allows a "bottom bulb" of aggregates to form at the bottom of the shaft, which causes lateral densification of the surrounding soil and establishes a densified aggregates layer at the bottom of the aggregates column. Thereafter, 12-inch lifts or layers of aggregates are placed and compacted typically to densities that equal or exceed 100 percent modified Proctor maximum dry density. The aggregates placement and compacting process must comply with ASTM D1241-00. With each 12-inch lift or layer, energy from the vertical impact of the tamper and hammer densifies and forces aggregates laterally into the matrix of the surrounding native soil, thus achieving densification and increased strength and stiffness in the surrounding soil and in the aggregates shaft.

12.8.4 Analysis Methods

As with all foundation designs, RAP shafts have to be evaluated for vertical load capacity and settlement, lateral load capacity and uplift load capacity. Analytical methods for Rammed Aggregates Piers have been based on the traditional geotechnical engineering procedures combined with evaluation of the shear strength and stiffness characteristics of the aggregates shafts.

12.8.4.1 Bearing Capacity of Rammed Aggregates Piers

As discussed in the previous section, RAP elements are constructed somewhat differently than conventional deep foundations, driven or augered piles and drilled piers or caissons due to the RAP's use of aggregates rather than concrete or steel to carry loadings. RAP's overall purpose is nonetheless similar to that of other types of deep foundations, which is to keep walls and footings of structures from experiencing excessive settlement. The same principles apply to calculate the bearing capacity for RAP elements. The traditional Terzaghi's equation is used to calculate the bearing capacity for spread footings supported on soils:

$$q_u = c'N_c + qN_q + \frac{1}{2}\gamma BN_\gamma \qquad (12\text{-}12)$$

The equation takes into consideration the effects of the unit weight of the soil, cohesion, and the surcharge. The terms N_c, N_q, and N_γ are the bearing capacity factors, which can be determined based on the internal friction angle of the soil (Das, 2002).

As for the bearing capacity of RAP elements, the Terzaghi equation, which was developed for shallow foundations, has been modified based on the potential limit equilibrium failures exhibited by RAP elements. The potential limit equilibrium failure modes for RAP supported footings consist of four types of failure: 1) bulging failure of individual RAP elements; 2) shearing below the tips of the RAP elements (similar to bearing beneath the tip of a pile); 3) shearing within the RAP-reinforced native soil; 4) and shearing below the bottom of the RAP-reinforced soil matrix. Observations and testing of the RAP/Geopier-elements were obtained by Dr. Kord J. Wissmann, P.E., chief engineer for Geopier Foundation Company, Inc. and by Professor Emeritus Richard L. Handy of Iowa State University and Professor George M. Filz of Virginia Tech.

When an individual Geopier element has experienced bulging failure, the shear strength is fully mobilized within the elements and along the surfaces extending through the surrounding soil matrix. Pressure applied to the top of a Geopier element causes this bulging. As stated by Wissmann (1999), the development of shearing surfaces within the Geopier elements cause the Geopier elements to bulge outward and the lateral earth pressure in the matrix soils around the Geopier elements resist outward bulging. The greatest amount of bulging occurs in the upper portion of the Geopier elements due to the fact that there is little lateral earth pressure in the surrounding soil matrix of the pier element as it gets closer to the ground surface.

In a technical bulletin provided by Wissmann (1999), Hughes and Withers had used cavity expansion theory to formulate an expression for the bearing capacity of single granular columnar elements subject to bulging deflections. An equation to determine the ultimate stress applied to the top of the Geopier element ($q_{ult,g}$) for bulging failure of individual Geopier elements was developed as:

$$q_{ult,\,g} = \sigma_{r,\,lim} \tan^2\left(45 + \frac{\phi_g}{2}\right) \qquad (12\text{-}13)$$

The equation estimates the ultimate stress at the top of the RAP element by taking into consideration the limiting radial stress and the Rankine passive earth pressure coefficient exerted on the aggregates material. The term ϕ)g is the friction angle of the aggregates material and $\sigma_{r,lim}$ is an estimated value of the limiting radial stress of the RAP element. The term for radial stress ($\sigma_{r,lim}$) can be determined using the following expression:

$$\sigma_{r,\,lim} = \sigma_{r,\,0} + c\left(1 + \ln\left(\frac{E}{2c\,(1+\mu)}\right)\right) \qquad (12\text{-}14)$$

The above expression uses the total radial stress ($\sigma_{r,lim}$) after the Geopier element has been installed and before the footing has been applied to the Geopier element. The undrained shear strength (c), the undrained modulus of the matrix soil (E), and Poisson's ratio of the matrix soil (μ). However, Equation 12-14 can be simplified as:

$$\sigma_{r,\,lim} = 2\sigma_v^3 + 5.2c \quad (12\text{-}15)$$

The simplification of Equation 12-15 was determined by the assumption of values for a cohesive soil matrix where the ratio of the undrained modulus (E) to the undrained shear strength (c) of the cohesive soil is estimated to be 200 and Poisson's ratio for undrained conditions to be 0.5. The use of this equation is based on the assumption that the effective stress friction angle is 20 degrees for saturated clay, and the additive influence of pore water pressure is neglected.

12.8.4.2 Settlement

Rammed Aggregates Pier elements often have been used to reinforce soils for support of MSE retaining walls and embankments fills for highways in addition to building foundations to prevent significant settlement from occurring. According to a study performed on Geopier elements for settlement control on MSE retaining walls and embankments for highways, rammed aggregates piers experience settlement in two zones: the upper zone and the lower zone. The upper zone of the element is considered as the settlement in the portion within the Geopier-reinforced zone. In the upper zone, the soil is significantly stiffened and compressed into what is known as an engineered zone or the aggregates pier influence zone. In a study by Lawton and Fox (1994), the upper zone consists of the composite soil zone plus the soil beneath the composite zone that is densified and prestressed during the construction process. The upper zone reduces the settlement for the intended structures. The lower zone, on the other hand, is the settlement below the element's reinforced zone. A simple equation calculating total settlement has been given as:

$$s_t = s_{uz} + s_{1z} \quad (12\text{-}16)$$

where

s_t = Total settlement of the transportation structures
s_{uz} = Settlement in the upper zone of the element
s_{1z} = Settlement in the lower zone of the element

As previously discussed, Geopier elements experience settlement and it is inevitable that structures will experience settlement of some sort. It is important to observe and determine the amount and time of settlement which occurs in a RAP element. To determine the total settlement in the Geopier reinforced zone, the following equation was developed to determine the settlement in the upper zone of the element:

$$q_g = q\left(\frac{n_s}{n_s R_a - R_a + 1}\right) \quad (12\text{-}17)$$

where

q_g = Stress at the top
q = The average applied bearing pressure
R_a = Ratio of the cross-sectional area coverage of the element to the matrix soil
n_s = Stress concentration ratio between the elements and the matrix soil

As a result, using Equation 12-17, the settlement in the upper zone of the element can be calculated by:

$$s_{uz} = \frac{q_g}{k_g} \quad (12\text{-}18)$$

where

k_g = The stiffness modulus in the RAP element.

Two types of expression can be applied when determining the settlement in the lower zone of a RAP element: the elastic modulus and consolidation. The expression to determine settlement for elastic modulus is applied to granular soils and/or heavily over-consolidated cohesive soils. The second expression for consolidation is applied to cohesive soil conditions where the soils have experienced normal-consolidation or are lightly over-consolidation. The equation below uses elastic modulus in the lower zone of the matrix soil to determine settlement in an element:

$$s_{lz} = \frac{\Delta q H}{E} \quad (12\text{-}19)$$

where

Δq = The average bearing pressure applied by the wall and embankment
H = Thickness of the lower zone
E = Matrix soil elastic modulus

The second equation uses consolidation of the lower zone soil to determine settlement:

$$s_{lz} = C_c\left(\frac{1}{1+e_o}\right) H\log\left(\frac{p_o + \Delta q}{p_o}\right) \quad (12\text{-}20)$$

where

Δq = The average bearing pressure applied by the wall and embankment
H = Thickness of the lower zone experiencing significant stress increase
C_c = Coefficient of compressibility in the matrix soil
e_o = Void ratio in the compressible lower zone soil
p_o = Vertical effective stress at the mid-point of the compressible layer

Although each equation is different in terms of calculation, both expressions use the average bearing pressure applied by the wall and embankment, Δq, to determine settlement in Geopier elements. The average bearing pressure is achieved by multiplying the applied pressure and the stress influence factor, I_σ, in which the stress influence factor is 1.0. This value is an assumption due to the fact of the large lateral extent of MSE walls and embankments.

12.8.4.3 Uplift Resistance

Uplift loads are a common dilemma for foundation systems. Rising structures above the ground surface are usually subjected to uplift (tensile) forces, or lateral loads. Horizontal earth pressures or natural events such as earthquakes and windstorms typically generate these forces. To prevent uplift forces on the footings and resist lateral loading, whether the Rammed Aggregates Pier element is individually placed or grouped with several other Rammed Aggregates Pier elements, uplift anchors are frequently installed during the preliminary construction phase. This allows the footings to resist compression and tensile forces, in addition to an increased stiffness from the rammed aggregates and the high friction angle of the aggregates compacted into native soils resists an overturning moment occurring at the building foundation.

According to a research conducted by the Geopier Foundation, uplift elements depend on a variety of circumstances to calculate the appropriate factor of safety. The primary factor depends on whether or not a load test is performed at the site, the second is the rate of anticipated loading applied to the structure, and finally, the direction of loading (Geopier Foundation Co. Inc., 2001). In most cases, uplift load tests are performed on Geopier elements where the soil is soft, loose and unstable. The factor of safety commonly used for typical design requirements in weak soil conditions is 2.0. This value is considered appropriate to resist uplift forces in a load tested RAP element. In special cases where an individual element or a group of elements may experience seismic forces, a lower factor of safety is considered due to the greater resistance of the anchors to dynamic loadings.

The construction techniques to installing uplift anchors within a RAP element are similar to constructing an element without uplift anchors. The anchors consist of a rectangular or round steel plate with threaded rods, which connect to the outer edge of the steel plate and extend to the top of the proposed footing. Once the cavity has been drilled to the appropriate depth, a bottom bulb is constructed at the bottom of the shaft and an uplift harness is lowered onto the top of the bottom bulb of the cavity. It is important that the rods connecting to the plate must have the appropriate spacing to allow the ramming of the aggregates with the hammer. As each 12-inch lift of aggregates is rammed, the anchors become secured and functional for the structure's footing.

12.8.5 Conclusion

Rammed aggregates piers are a quick and economical solution to stabilizing poor soils that are unsuitable for engineering purposes. It is a flexible alternate method as opposed to the conventional methods of augered cast-in-place piles, pile driving, drilled piers, etc. This process helps to increase the stiffness and stability in soils by improving the friction angle of the surrounding soil, as well as decreasing settlements for foundations, thus increasing the factor of safety.

12.8.6 Introduction to Stone Columns

The stone column method is a geotechnical solution to reinforce and stabilize weak soils by the dense compaction of aggregates materials into cylindrical cavities. It is a method with behavioral functions similar to rammed aggregates piers in a sense that the stone column method increases bearing capacity and decreases liquefaction potential and settlement in the surrounding soil. To act as a deep foundation element, stone columns need to penetrate through soft soils and bear on hard, dense strata. Soils that may be improved by the stone column method include cohesive soils such as soft clays and silts with fines greater than 15 percent, as well as loose granular soils such as silty sand.

Historically, stone columns, which also are known as 'vibrated stone columns,' were used extensively in the 1930s to densify granular soils in the United States, Europe, Asia and Africa. Thirty years later, the stone column method, originally applied to strengthen granular soils, has been applied to cohesive soils as well. Today, the popular stone column method is used as an alternate geotechnical solution to pile driving, augered cast-in-place piles, and drilled piers, and has been applied to various projects involving embankments, pavement and foundation designs in addition to railroad and wharf structures.

12.8.6.1 Construction of Stone Columns

There are two general types of stone columns: end bearing columns and floating columns. End bearing columns are columns constructed on firm strata. The base of the stone column rests on firm strata such as bedrock, highly consolidated sand layers or highly over-consolidated clay layers. Floating columns are constructed in soft strata and do not bear on firm strata for support. Floating columns commonly are applied to subsoil conditions where firm strata are too deep or the firm strata are not thick enough to support the stone column.

The construction of stone columns is based on several processes. In this section, only three of these processes will be discussed. Two of these processes are considered to be conventional methods when constructing stone columns. These methods involve the use of water or air to laterally displace the matrix soil to create a cylindrical cavity. These two processes are known as the 'wet method' and the 'dry method,' and are widely used on most engineering projects. The third method of stone column construction is accomplished by boring a hole or driving an open- or closed-end pipe into the subsoil.

The first process is the wet method, also known as the vibro-replacement method. This method of stone column construction is accomplished by using water to form the hole. At the beginning of construction of the hole, a probe is driven into the ground to the desired depth as water is exerted from the probe with jet-like forces to 'flush out' or laterally displace the matrix soil. This technique is applied to situations where shallow water tables exist at the site or the soil is very soft to firm in density.

In contrast, the dry method is accomplished by using air pressure to form the hole. The dry method often is referred to as vibro-displacement method. This method uses high-pressure air to displace or remove fine particles of the soil. Depending on the condition of the subsoil at the site, that is how loose or soft the soil is around the hole, the hole may collapse as the probe is extracted from the hole. For this reason, experts believe the subsoil at the site must possess shear strengths of approximately 850 to 1,250 pounds per square foot (psf) and the groundwater at the site must be below the stone column for proper application of the "dry" construction method (Barksdale, 1983).

The third process for construction of stone columns involves driving a pipe into the subsoil. This pipe may be an opened- or a closed-end pipe. The process of driving a casing to form the hole eliminates caving and potential collapse inside the cavity; therefore the process is generally accepted for most types of soils.

Once a construction method has been determined, the initial phase of construction begins with a vibrating probe that penetrates to the recommended depth using either the dry or wet process. The vibrating probe is cylindrical in shape, approximately 14 to 18 inches in diameter, and 7 to 15 feet long. The size of the vibrating probe and the pressure of the water or air exerted by the probe vary, and are dependent on the site subsoil conditions. The vibrating probe consists of a hydraulic or electric motor inside the cylindrical casing. The vibrating probe is quite heavy and must be used with crane and boom equipment. The typical equipment sizes to handle a vibrating probe consist of a 40-ton crane with a 40-foot boom.

Formation of the cavity begins when the vibrating probe streams water or air with intense pressure to displace the soil. Once the vibrating probe is inserted into the ground, the probe penetrates into the ground by the vibrations from the compressed air or water exerted from the probe as well as from its own weight. The soil displaces laterally and compacts at the sidewalls of the cavity thus increasing the density of the surrounding soil. When the cavity has achieved the desired depth, it is 'flushed out' two to three times to remove weak soils like as clay, silt and organic particles.

After completion of the cavity, aggregates "stones" are ready to be placed and compacted. The stone column must sustain a solid base to achieve it performance qualities. According to a technical paper by the Nicholson Construction Company, there are three methods of placing aggregates "stones" into the cavity: the dry top-feed stone column installation; the dry bottom-feed stone column installation; and the wet top-feed stone column installation. These methods depend on the subsoil conditions, groundwater levels, soil classification as well as the equipment used by the stone column contractor.

The dry top-feed method is applied to prevent collapse of the cavity. This method is applied to subsoils with shear strengths greater than 850 pounds psf, no presence of groundwater and/or no potential for migration of groundwater to infiltrate the stone column. It is crucial that the surrounding soil have enough shear strength to avoid collapse or partial collapse once the vibrating probe is fully removed from the cavity. When the vibrating probe is completely removed from the cavity, aggregates are placed at the bottom of the cavity and compacted by reinserting the vibrating probe. As the vibrating probe is raised to the surface, stones are placed in 24- to 36-inch lifts in the cavity to densify the surrounding soil. The compaction of the stones in the cavity are achieved by the pulsating motion of the vibrating probe which can result in reduced void spaces to create a tighter interlocking contact between each stone. This procedure of removing the vibrating probe and placing stones in 24-, 36-, or 48-inch lifts is repeated several times until the column has reached the compaction criteria at each lift. The repeating process is not complete until the column of stone has reached the surface.

The dry bottom-feed stone column installation, on the other hand, utilizes a tremie pipe. This method is normally applied to subsoils with a shear strength ranging between 150 to 850 pounds psf, no presence of groundwater and/or no potential for the migration of groundwater to infiltrate the stone column. The tremie pipe is mounted to the side of the vibrating probe. This allows the stones to be placed at the bottom of the cavity without completely removing the vibrating probe. The vibrating probe is raised high enough to prevent collapse of the sidewalls of the cavity while stones are placed into the tremie pipe and transferred to the bottom of the column. Once the specified amount of stones has been placed at the bottom of the cavity, the vibrating probe compacts to achieve densification of the stone column as it is slowly lifted to the surface.

The third installation method is known as the wet top-feed installation. The wet top-feed installation method uses water instead of air to laterally displace the soil to form the cavity and often is used at sites where the ground water table is shallow and the possibility of the migration of water is high. The vibrating probe penetrates the soil similarly to the dry top-feed and dry bottom-feed installation methods, but uses jet-forced water to compact the surrounding soil and flush loose soil from the hole to the desired depth. By use of the wet-top feed installation method, the vibrating probe can be removed completely from the hole. The chances of collapse and partial collapse are small due to the fact that the water acts as a binder between the soil particles to prevent collapsing of the sidewalls. Once the vibrating probe has been entirely removed, stones can be placed at the bottom. The stones are further compacted by use of the vibrating probe as it is lifted to the surface. The process of adding stones in lifts and compacting with the vibrating probe is repeated until the recommended compaction is achieved and the column has reached the surface. This process is similar to the dry top-feed installation method.

12.8.6.2 Aggregates Specifications for Stone Columns

Stone columns are constructed with sand, gravel and open-graded stone. Specification of the stones must include a high degree of durability. In addition, the stones must be clean and free of organic material, debris and other harmful materials.

Specifications provided by the Federal Highway Administration, recommend the size of stones between 0.5 to 3.0 inches in diameter. Specification of diameter of stones used in the stone column method is often project specified based on local experience. However, laboratory testing of the stone column aggregates is required. Four laboratory tests required by the Federal Highway Administration for stone column aggregates include the gradation test in accordance with AASHTO T-27; the specific gravity test in accordance with ASTM C127; the density of loose stone in accordance with ASTM C29; and the density of compacted stone in accordance with ASTM C29. Stone column aggregates requirements vary depending on the depth and diameter of the cavity, and the durability and specific weight of the stones with respect to the subsoil conditions. A table is provided by the Federal Highway Administration (FHWA) giving four alternative recommendations for choosing gradation type of the stones based on the subsoil conditions. This table is given in 12.12 below.

Table 12.12 Gradation Recommendations for Stone Columns

Sieve Size (Inches)	Alternate No.1 Percent Passing	Alternate No. 2 Percent Passing	Alternate No. 3 Percent Passing	Alternate No. 4 Percent Passing
4	—	—	100	—
3.5	—	—	90-100	—
3.0	90-100	—	—	—
2.5	-	—	25-100	100
2.0	40-90	100	—	65-100
1.5	—	—	0-60	—
1.0	—	2	—	20-100

According to the FHWA, Alternate No. 1 and Alternate No. 2 are the most common recommendations for construction of stone columns, and they are appropriate for most subsoil conditions. Alternate No.2; however is applied to subsoil conditions containing soft layers of organic material. In situations where Alternate No. 2 are not feasible according to the subsoil conditions, Alternate No. 3 may be applied but only if Alternate No. 1 and 2 are not appropriate. In special cases, Alternate No. 2 and 4 are applied if the stones are not large enough based on recommended sizes for Alternate No. 1.

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Chapter 13

Impact of Properties of Aggregates on Pavement Design and Analysis

Using the American Association of State Highway and Transportation Official's Mechanistic-Empirical Pavement Design Guide

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13.1 Introduction

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is the result of National Cooperative Highway Research Program (NCHRP) project 1-37A and computes responses to traffic loads under specific environmental conditions. These responses are translated to damage and ultimately distress through mechanistic-empirical "transfer functions." In this sense the term transfer function means that a mechanistic response, i.e., stress, strain or deformation, is translated to fatigue damage or permanent deformation (rutting). In most cases a layered elastic computer program or layered elastic analysis (LEA) computes responses of a layered pavement system to simulated static wheel loads. In a more sophisticated analysis available within MEPDG, the layered pavement structure can be modeled using finite element analysis (FEA). This model allows responses to be computed at various element nodes considering stress sensitivity of the unbound aggregate and soil layers, which varies within these layers as a function of depth and in transverse and longitudinal directions.

Traffic loads in MEPDG are input in terms of axle load distribution by axle configuration and traffic volume within each axle category throughout the day. In fact the number of axles by configuration and weight are accounted for in hourly increments.

Fatigue Damage and Cracking Distress

Two forms of fatigue damage are addressed in MEPDG: bottom-up fatigue cracking and near-surface cracking. The first step in either approach is to compute the number of axle loads in each category that will cause consumption of fatigue life, Nf .The transfer function for Nf used in MEPDG is a variation of the function developed by Finn et al. (1986):

$$N_f = 0.00432\, k_1' C \left(\frac{1}{\varepsilon_t}\right)^{3.9492} \left(\frac{1}{E^*}\right)^{1.281} \qquad [13\text{-}1]$$

Where ε_t is the tensile strain in the lower portion or bottom of the composite asphalt concrete (AC) layer, E* is the dynamic modulus of the AC layer, k_1' is a calibration constant, and $C = 10^M$ is an adjustment factor to account for the impact of AC mixture volumetrics on fatigue. In this case,

$$M = 4.84\left(\frac{V_b}{V_a + V_a} - 0.69\right) \qquad [13\text{-}2]$$

Where V_b is the volume of the binder and V_a is the volume of the air as percentages of the total volume of the AC mix. The coefficient k_1' is a function of the thickness of the AC layer in inches and is incorporated largely to account for the shift from fatigue characteristics that occur in a controlled-strain mode for very thin AC layers (and for which equation [13-1] applies when

$k_1' = 1.0$) and transition, sigmoidally (as the k_1' function represents), to a controlled-stress mode for thick pavements.

Fatigue damage (FD) as a percent is accumulated separately for bottom-up and near-surface cracking using minor's hypothesis:

$$FD = \sum \frac{n_{i,j,k,l,m}}{N_{i,j,k,l,m}} \quad [13\text{-}3]$$

Where

- ni, j, k... = Applied number of load applications at conditions i, j, k, l, m...;
- Ni, j, k... = Number of axle load applications to fatigue failure or total consumption of fatigue life under conditions i, j, k, l, m;
- i = Month and accounts for moduli changes in soil and aggregates layers due to moisture and temperature variation;
- j = Time of day, which accounts for hourly changes in modulus of the AC;
- k = Axle type;
- l = Load level for each axle type; and
- m = Traffic path, assuming a normally distributed lateral wheel wander.

The enhanced, integrated climatic model (EICM) is used to compute hourly changes in temperature and other weather data from the site in question. Once a series of layered elastic solutions are performed to complete the analysis for the various axle loads and environmental conditions that represent the specific situation being simulated, cumulative fatigue damage is summed, FD. This damage, or consumption of fatigue life, is then translated to distress in terms of percent the total lane area cracked, FC. The form of this function is:

$$FC = \frac{100}{1 + e^{c_2'(-2 + \log FD)}} \quad [13\text{-}4]$$

Where c_2' is a function of the depth of the AC layer. Near-surface fatigue cracking is calculated by using the same fatigue damage transfer function used for bottom-up cracking, equation [13-1] and a similar sigmoidal distress function to transform from damage to observed cracking distress. Locations for critical near surface bending strains are defined at points at varying distances from the wheel load area of application and where counter flexure of the asphalt layer is likely to occur resulting in tensile strains near the surface of the AC layer, typically between the surface and a depth of one-half inch. Shear stresses, which are most often associated with near surface cracking near the AC surface and very near or contiguous to the tire edge cannot be accurately determined in the LEA mode. Therefore responses are computed by LEA deeper within the AC layer and a linear extrapolation technique is used to approximate surface strains as input data for the transfer functions.

Distress Due to Rutting

MEPDG sums plastic deformation (PD) in each sublayer of the pavement:

$$PD = \sum_{i=1}^{n} \varepsilon_p^i h^i \qquad [13\text{-}5]$$

Where ε_p^i is the plastic strain in sublayer i, h^i is the thickness of the sublayer i and n is the number of sublayers. Since the models incorporated into MEPDG are not capable of directly calculating plastic strain, empirical algorithms are used. In the case of the AC layer or AC sublayers, the ratio of plastic strain to vertical total resilient strain, ε_v, a response computed by the LEA or FEM, is determined by an algorithm based on empirical data as a function of temperature, T, and number of load applications, N:

$$\frac{\varepsilon_p}{\varepsilon_v} = k_1 10^{\beta_1 -3.4488} T^{\beta_2 1.5606} N^{\beta_3 0.479244} \qquad [13\text{-}6]$$

Where the β_i field or site factors are calibration factors and k_1 is an adjustment factor that accounts for the increased level of confinement with depth. The ratio $\frac{\varepsilon_p}{\varepsilon_v}$ in equation [13-6] is related to N as a continuous function, and the rate of accumulation of ε_p with loading cycles increases as temperature increases and decreases when temperature decreases. Therefore, at the end of each seasonal increment, a corrected or equivalent number of load applications, $N_{i\ equiv,}$. is determined and the loading cycles are adjusted from that point for subsequent seasons to develop the value of ε_p^i at the appropriate rate as a function of the temperature conditions in subsequent seasons.

Plastic strain in the unbound aggregate base (UAB) and unbound aggregate subbase (UAS) layers as well as in the subgrade soil is determined using the Tseng and Lytton (1985) model, which relates plastic strain, ε_p, to vertical elastic, resilient strain, ε_v, calculated from the LEA or FEA:

$$\frac{\varepsilon_p}{\varepsilon_v} = \beta_G \left(\frac{\varepsilon_0}{\varepsilon_r}\right) e^{-\left(\frac{\rho}{N}\right)^{\beta}} \qquad [13\text{-}7]$$

Where β, ρ, and ε_0 are material properties obtained from laboratory testing involving repetitive loading at resilient strain level, ε_r, and N is the number of load repetitions. Although equation [13-7] is based on empirical laboratory testing, for convenience, the values of β, ρ, and $\frac{\varepsilon_0}{\varepsilon_r}$ can be approximated for base and subbase layers as a function of moisture content and assuming that these layers meet specification requirements regarding material quality and construction methods.

The general forms of β and ρ are given as follows:

$$\log\beta = -0.6119 - 0.017638 W_c$$
$$\rho = 10^9\left(\frac{-4.89285}{1-\left(10^9\right)^{\beta}}\right) \quad [13\text{-}8]$$

Where W_c is moisture content in percent. The ratio is computed as the weighted average of experimental measurements after 1 and 109 loading cycles:

[13-9]

Pavement permanent deformation is then the sum of the incremental plastic deformations computed within each pavement sublayer as shown in equation [13-5]. To accomplish this each layer is typically divided into sublayers. The rutting in the subgrade is accumulated from the surface of the subgrade to bedrock according to equation [13-10]. A simplifying assumption is made based on the rate of dissipation of vertical plastic strain in the subgrade (computed from equation [13-7]). This is defined by a factor k, which is computed based on the values of vertical plastic strain at the top of the subgrade and at 6-inches below the surface of the subgrade under specific traffic axle loads and configurations.

$$\delta = \varepsilon_{p,z=0}\int_0^{h_{bedrock}} e^{-kz}\,dz = \left(\frac{1-e^{-kh_{bedrock}}}{k}\right)\varepsilon_{p,z=0} \quad [13\text{-}10]$$

Transverse Cracking

Transverse cracking due to thermal fluctuations in the AC layer is predicted based on a simplified fracture mechanics approach in which thermal cracking is initiated when the thermal stresses exceed the tensile strength of the AC. Once this occurs, the change in crack length, ΔC, is tracked using Paris's law:

$$\Delta C = A\Delta K^n \quad [13\text{-}11]$$

Where A and n are material properties and ΔK is the change in stress intensity factor, which is related the change in stress, σ, for each thermal cycle. ΔK is a function of σ and original crack length, C_0. The fracture properties, A and n are derived from tensile creep test data.

Material properties of the AC layer for the thermal cracking analysis are measured in a tensile creep test in which slow loading rates, which simulate the duration associated with thermal cycles, are applied at low temperatures. A generalized Voight-Kelvin model is fitted to the tensile creep master curve. Here the creep compliance is expressed in terms of reduced time. This function is then transformed into the frequency domain and the stress relaxation modulus is expressed in the frequency domain. From here a reverse LaPlace transformation is used to calculate the AC relaxation modulus in the time domain. This allows one to compute stresses as a function of change in temperature and/or time of loading using Boltzman's superposition principle.

The tensile compliance properties that form the basis for these calculations are not very sensitive to aggregates properties, but instead are dominated by binder and mastic properties. For this reason, the overview of the thermal cracking approach is limited in this chapter.

General Performance

In the 1993 AASHTO Pavement Design Guide and in previous versions of the AASHTO Guide the serviceability concept is used. However, in the MEPDG, the international roughness index, IRI, is used and is related to distress through a regression model. Several versions of the IRI v. computed distresses (as the main independent variables) are presented in the MEPDG which represent several different flexible pavement structural types. The following model is used for asphalt concrete pavements on unbound granular bases:

$$IRI = IRI_0 + 0.0463\,SF\left(e^{age/20} - 1\right) + 0.00119\,TC_T + 0.1834\,COV_{RD} + 0.00384 + FC + 0.00736\,BC + 0.00115\,LC_s \quad [13\text{-}12]$$

where IRI_0 is the initial pavement roughness, TC_T is the total length of transverse cracks, COV_{RD} is the coefficient of variation in rut depth, FC is the fatigue cracking in the wheel paths, BC is the area of block cracking (percent of total lane area), age is the age of the section (years), and SF is the site factor computed as a function of annual rainfall and subgrade index properties such as percent silt and clay sized particles and plasticity index.

13.2 Characterization of the Asphalt Concrete Layers

The dynamic of the AC sublayers is probably the single most important engineering property of the AC layer in MEPDG. This is because in order to compute pavement responses to load, which are used in computing fatigue and rutting damage within all pavement layers, reliable layer moduli are required. Furthermore, in the constitutive relationships required for layered elastic analysis, upon which the MEPDG structural analysis is based, layer moduli along with layer Possion's ratios are required.

Since the modulus of the AC layer and/or sublayers is time and temperature dependent, the dynamic modulus was selected as the type of modulus for the AC layers. The dynamic modulus is measured by imparting a sinusoidal stress pulse to a cylindrical AC sample. The test is conducted over a range of combinations of frequency of the sinusoidal pulse temperature in order to cover the range of frequencies and temperatures representative of the pavement environment. The procedure for dynamic modulus testing under compressive loading is presented in a provisional standard, AASHTO TP 62. In this procedure the peak stress level maintains a total measured strain of between 50 and 150 microstrain, which has been determined experimentally to be within the linear viscoelastic range of AC mixtures used for pavements. Although a creep effect is induced in the cyclic loading, it is ignored and only the dynamic modulus is measured as the ratio of the amplitude of the stress function to the amplitude of the dynamic strain function.

Data obtained from the dynamic moduli tests over a range of frequencies and for various temperatures are used to construct a master curve for the AC mixture. MEPDG recommends the use of a sigmoidal function to describe the master curve:

$$\log|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma\log t_r}} \qquad [13\text{-}13]$$

Where t_r is reduced time (where time may be considered to be the reciprocal of frequency), which is defined as at the reference temperature, δ is the minimum value of $|E^*|$, $\delta + \alpha$ is the maximum value of $|E^*|$, and β and γ are parameters which describe the shape of the sigmoidal function. These parameters are expressed within MEPDG as functions of mixture volumetrics and gradation. In Level 1 of MEPDG the master curve is the result of dynamic modulus testing at temperatures of 10, 40, 70, 100 and 130°F (-12, 4, 21, 38 and 54°C) and for each temperature at frequencies of 0.1 Hz, 1 Hz, 10 Hz and 25 Hz.

Values of δ and α in equation [13-13] can be calculated based on certain properties of the aggregate and mixture as follows:

$$\delta = -1.249937 + 0.02932\,\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\,\rho_4 - 0.05809\,V_a - 0.802208 \qquad [13\text{-}14]$$

$$\left[\frac{V_{b_{eff}}}{V_{b_{eff}} + V_a}\right] \qquad [13\text{-}15]$$

Where

V_a = Air void content, %

$V_{b\,eff}$ = Effective bitumen content, % by volume

$\rho_{3/4}$ = Cumulative % retained on the ¾ inch sieve

$\rho_{3/8}$ = Cumulative % retained on the ⅜ inch sieve

ρ_4 = Cumulative % retained on number 4 sieve

ρ_{200} = Cumulative % passing the number 200 sieve

In Levels 2 and 3 of MEPDG the dynamic modulus can be predicted over a range of temperatures, rates of loading and aging conditions from information that is readily available from material specifications or volumetric design of the mixture:

$$\log E^* = -1.249937 + 0.02932\,\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\,\rho_4 - 0.05809\,V_a$$
$$-802208\left[\frac{V_{b_{eff}}}{V_{b_{eff}} + V_a}\right] + \frac{3.871977 - 0.0021\,\rho_4 + 0.003958\,\rho_{3/8} + 0.005470\,\rho_{3/4}}{1 + e^{(-0.603313 - 0.31335\log(f) - 0.393532\log(\eta))}} \quad [13\text{-}16]$$

Where η = viscosity, x106 Poises; f = loading frequency, Hz.

13.3 Resilient Properties for Level 1 Analysis

Resilient Modulus Model

Impact of Stress State

The MEPDG offers two options for structural analysis: layered elastic analysis, LEA; and finite element analysis, FEA. The analysis period is divided into 1-month or 2-week increments. At the end of each increment pavement responses are determined. In the LEA module, one modulus value is used for each structural layer, and this is determined by multiplying the value of the reference modulus for the UAB by a correction factor for the environmental effects for that period, Fenv. The Fenv value is generated by the enhanced integrated climatic model (EICM) for the specific layer and analysis increment. The reference modulus for the layer being considered is the resilient modulus at optimum moisture content and maximum dry density (MRopt) conditions which are normally achieved at construction but which can rapidly change based on environmental factors. The LEA in MEPDG does not account for the stress state in the UAB. However, a reasonable approximation of the stress state within each UAB layer or sublayer can be made with the help of a LEA and an appropriate resilient modulus for the UAB layer or sublayer can be estimated based on AASHTO T-307 or NCHRP 1-28 protocol. Table 2 is a reproduction of a table from the *1986 AASHTO's Guide for the Design of Pavements* and provides an approximate estimate of bulk stress, θ, for typical pavement conditions. Based on this approximation for the bulk stress the modulus can be calculated from as:

$$M_R = k_1\,\theta^{k_2} \quad [13\text{-}17]$$

Values of k_1 and k_2 depend on the quality of the aggregate base (gradation, percent materials smaller than 75 μm, plasticity of fines, angularity of aggregates, surface texture, shape and form, etc.) and the moisture state. Approximate values of k_1 and k_2 are presented in Table 2.

Table 13.1 Typical values of θ for base courses.

Asphalt Concrete (AC) thickness, in.	Roadbed Soil Resilient Modulus, psi		
	3,000	7,500	15,000
< 2	20	25	30
2 – 4	10	15	20
4 – 6	5	10	15
>6	5	5	5

Table 13.2 Approximate values of k_1 and k_2 for good quality aggregates base and subbase.

Moisture Condition	k_1	k_2
Unbound Aggregates Base (typically CBR ≥ 100%)		
Dry	6,000 – 10,000	0.5 – 0.7
Damp	4,000 – 6,000	0.5 - 0.7
Wet	2,000 – 4,000	0.5 – 0.7
Unbound Aggregates Subbase (typically CBR ≥ 30%)		
Dry	6,000 – 8,000	0.5 – 0.6
Damp	4,000 – 6,000	0.5 - 0.6
Wet	1,500 – 4,000	0.5 – 0.6

In the FEA module, a finite element analysis is performed for each time period, and the resilient modulus at each node of the FEM mesh is determined for the stress state at that point and, in turn, modified by the corresponding value of Fenv. The equation used to compute the stress-dependent modulus in the finite element analysis is:

$$M_R = F_{env} \cdot k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \qquad [13\text{-}18]$$

Where

- MR = Stress dependent resilient modulus for the finite element being considered;
- F_{env} = Composite environmental adjustment factor for the layer/sublayer of which the finite element being considered is a part;
- k_1, k_2, and k_3 = Regression constants;
- p_a = Atomospheric pressure;
- θ = Bulk stress; and
- τ_{oct} = Octahedral shear stress

Environmental Effects – Frozen Aggregates Base

The general F_{env} factor is comprised of three components: factor for frozen materials, F_F; factor for recovering materials, FR; and factor for unfrozen materials, F_U. The F_F is computed at each node at which a freezing temperature occurs. The value for F_F is equal to $\frac{M_{R\,frz}}{M_{R\,opt\,est}}$, and the frozen modulus is a function of the product of the percent by weight of material smaller than the number 200 sieve, P_{200}, and the plasticity index of the fines (smaller that number 40 sieve size fraction), $P_{200}PI$. If this product is zero, then the value of $M_{R\,frz} = 2.5 \times 10^6$ and if the value of this product is greater than zero, $M_{R\,frz} = 1.0 \times 10^6$.

Environmental Effects — Recovering (from Frozen Conditions) Aggregates Base

The adjustment factor for recovering materials is computed at each node at which freezing temperatures do not occur. It is a function of the recovery ratio, RR; the recovery factor, RF; and the ratio of the equivalent resilient modulus to the optimal resilient modulus, R_{equil}. The recovery ratio, $RR = \frac{\Delta t}{T_R}$ and Δt is the number of hours elapsed since thawing began, and T_R is the length of the recovery period, which is a function of $P_{200}PI$. The RF for coarse-grained materials (P_{200}< 50%) is a function of gradation and PI, and is a larger value for coarser and less plastic aggregates. The value of F_R is a function of RR and RF with higher values of each rendering a higher value of the recovering material.

Finally, the value of R_{equil} is determined from equation [13-19]

$$\log R_{equil} = \log \frac{M_{Requil}}{M_{Ropt}} = a + \frac{b-a}{1+\exp\left[\ln\left(-\frac{b}{a} + k_m\left(S_{equil} - S_{opt}\right)\right)\right]} \qquad [13\text{-}19]$$

Where a, b and k_m are constants.

If the $(S_{equil} - S_{opt}) < 0$, then R_{equil} is > 1 or if $(S_{equil} - S_{opt}) > 0$, then R_{equil} is < 1. Furthermore, if $(S_{equil} - S_{opt}) < 0$, then $F_r = RF + R_{equil} \cdot RR - (RR \cdot RF)$); and if $(S_{equil} - S_{opt}) > 0$, then $F_r = R_{equil}$ (RF + RR – (RR • RF)). The MEPDG provides much more detail in determining specific values for a, b, and k_m as well as much more explicit instructions for approximating modulus values.

The reference condition for M_R is optimum moisture content, $w = w_{opt}$ and maximum dry density, γ_{dmax} under the specified compaction protocol. This is because it is common practice to require contractors to compact bases to at least 95 percent of AASHTO T180 or T99. Moisture content is rarely controlled strictly by specification, but good construction practice will force contractors to approach optimum moisture conditions. This MEPDG holds that $w = w_{opt}$ and maximum dry density, γ_{dmax} are reasonable assumptions for reference conditions.

It is, however, reasonable to assume that S changes (increases or decreases) to and equilibrium value, S_{equil} with time and that S_{equil} can be computed using the EICM considering the depth of the ground water table, γ_{GWT}, and the soil-water characteristic curve, SWCC. The value of S_{equil} does not actually depend on the initial S; but since S_{opt} is chosen as the reference point, the change from S_{opt} to S_{equil} is what must be considered. The protocol for making the best estimate of M_R under equilibrium conditions is:

1. Estimate or measure M_R at optimum conditions to get M_{Ropt}.
2. Estimate or measure S_{opt}.
3. Use the EICM to compute S_{equil}.
4. Use (S_{opt} – S_{equil}) to evaluate the change in M_R from the reference condition (M_{Ropt}) to the final, equilibrium conditions (M_{Requil}).

Using the above approach means that some inaccuracies may be expected in computing MR between the time of construction and time at which M_{Requil} is achieved, t_{equil}. However, the MEPDG states that according to their findings tequil are hours or days for most coarse-grained materials and weeks for the great majority of fine-grained materials. This durations is very short compared to the life of the pavement.

Figures 13.1 and 13.2, taken from MEPDG, illustrate how equation [13-19 changes as the relative level of saturation changes from optimal (normally at the time of construction) to an equilibrium condition that is expected to occur shortly following construction. It can further be used to illustrate how seasonal fluctuations in the moisture state (level of saturation) can incrementally influence the resilient modulus as seasonal moisture changes influence the modulus.

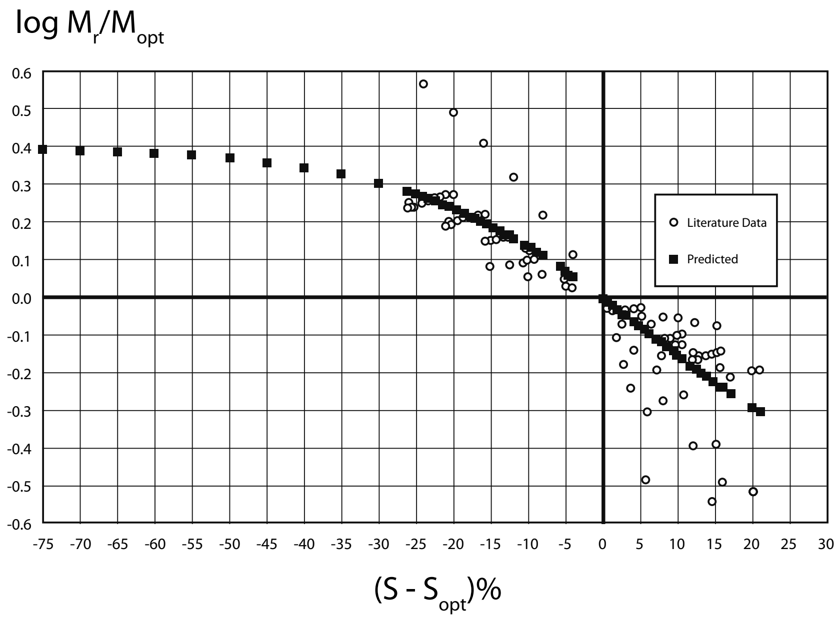

Figure 13.1 Relationship between resilient moduli and degress of saturation for fine-grained soils (modified from 1-37a NCHRP Design Guide of New and Rehabilitated Pavement Structures, March, 2004).

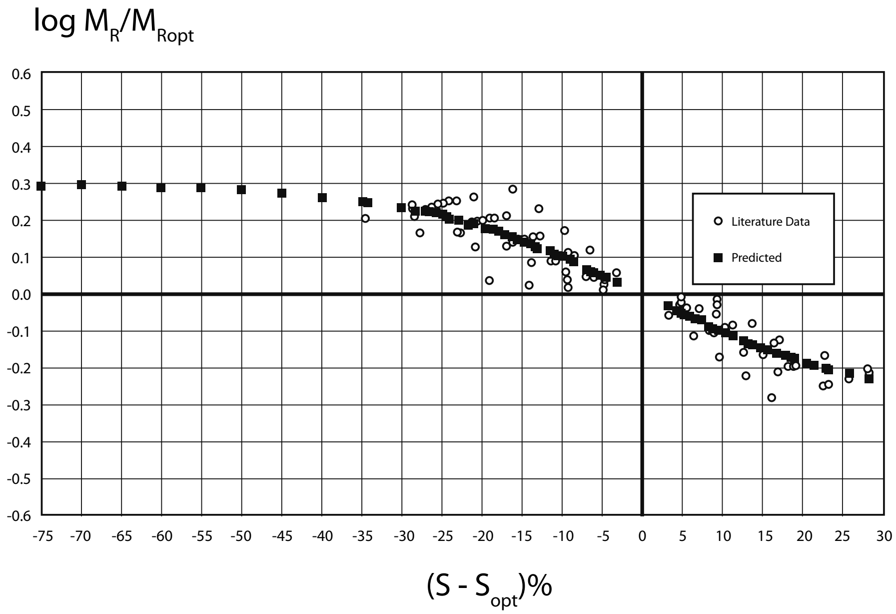

Figure 13.2 Relationship between resilient moduli and degree of saturation for coarse-grained soils and aggregates (modified from 1-37a NCHRP Design Guide of New and Rehabilitated Pavement Structures, March, 2004).

Environmental Impact on Resilient Modulus in FEA

MEPDG in the FEM mode computes a composite resilient modulus, MR comp and a composite environmental factor for each layer or sublayer, $F_{env\ comp}$. This is described in detail in the MEPDG, but is too tedious to be instructive in this chapter. However, Figure 13.3 taken from MEPDG demonstrates that different environmental conditions based on the temperature and moisture state define various environmental factors at the different nodes in the base and subbase sublayer and at the different points in time for a 14-day analysis period.

LEGEND:
FROZEN
RECOVERING
UNFROZEN

Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
	Time (days)														
3	50	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	BASE
4	50	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	F_{env} = 1.45
5	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
6	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
7	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
8	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
9	75	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	SUBBASE
10	75	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	F_{env} = 0.92
11	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	
12	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	
13	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	
14	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	
15	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	1	
16	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	1	1	1	

Figure 13.3 Representing values for unfrozen soil factors, F_U, frozen soils, F_F, and recovering factors, F_R.

The values assigned for each at each time node and depth node is determined as a function of soil properties, thermal condition and moisture condition. The values are ratios of the modulus at the specific node compared to M_{Ropt}. Note that a weighted average value, F_{env} for each layer is calculated (modified from 1-37a NCHRP Design Guide of New and Rehabilitated Pavement Structures, March, 2004).

Appendix A tabulates input data from unbound aggregates base materials for use in MEPDG. These input data presented in Appendix A are summarized in Table 13.3.

Table 13.3 Data required in MEPDG for aggregate base material.

Property	Purpose	Where Found
Specific gravity Optimum gravimetric water Unit weight of solids	Mass-volume calculations	Table A-1
Percent passing no. 200 sieve (P_{200}), size of sieve of which 60% of particles are smaller (D_{60}), plasticity index (PI), saturated permeability (k_{sat})	Saturated hydraulic conductivity K_{sat} To compute drainage characteristics	Table A-2
Soil classification Heat capacity	Dry thermal conductivity	Table A-3
Soil matric suction Gravimetric water content Dry unit weight Fitting functions for soil water characteristic curve (SWCC) PI P_{200} D_{60} Specific gravity of solids	Parameters to develop SWCC to be used in relating matric suction to degree of saturation and ultimately to be able to develop change in resilient modulus as a function of degree of saturation (S_{opt} – S_{equil})	Table A-4
P_{200} PI D_{60}	Adjustment factors for frozen materials	Table A-5
Recovery ratio, RR S_{equil} p_{200} PI D_{60} Percent passing no. 4 sieve, p_4	Summary of Computations made by EICM to determine adjustment factors for recovery of material	Table A-6
P_{200} PI P_4	Recommended values of recovery factor, RF, for coarse and fine grained soils	Table A-7 and A-8

Material Parameters in MEPDG

The material parameters required in MEPDG for unbound granular materials may be classified into one of the three major groups:

- Pavement response model material inputs
- EICM material inputs
- Other material inputs

Pavement Response Model

The pavement response model material inputs require resilient modulus and Poisson's ratio. Resilient modulus is required to calculate structural responses. It can be measured directly or computed internally by MEPDG software or derived by correlation with surrogate tests such as California Bearing Ratio (CBR).

Level 1 – Laboratory Testing

Resilient moduli are measured directly by testing protocols and then adjusted for seasonal variation as determined by the EICM. This is discussed in the preceding sections. The recommended test methods for modulus testing in level 1 are:

- NCHRP 1-28A, "Harmonized Test Methods for Laboratory Determination of Resilient Modulus for Flexible Pavement Design."
- AASHTO T-307, "Determining the Resilient Modulus of Soil and Aggregate Materials."

Level 2 – Correlations with Other Material Properties

For level 2 MEPDG software allows users to follow two options:

- Input a representative value of M_r and use EICM to adjust it for the effect of seasonal climate (i.e., the effect of freezing, thawing, etc.)
- Input M_r for each month (season) of the year (total of 12 months)

The primary use of the EICM is to estimate the temperature and moisture profiles within the pavement system throughout the pavement's design life. Users have the option of modifying the M_r values directly to account for seasonal changes in temperature and moisture. Table 4 provides some guidance in approximating modulus values from material index and strength properties.

Table 13.4 Models relating material index and strength properties to M_r.

Strength/Index Property	Model	Comments	Test Standard
CBR	Mr (in psi) = 2555 $(CBR)^{0.64}$	CBR = California Bearing Ratio, percent	AASHTO T193, "The California Bearing Ratio"
R-value	$M_r = 1155 + 555R$	R = R-value	AASHTO T190, "Resistance R-Value and Expansion Pressure of Compacted Soils"
AASHTO Layer Coefficient	M_r (in psi) = $30{,}000\left(\frac{a_i}{0.14}\right)^{(20)}$	a_i = AASHTO layer coefficient	AASHTO T27, "Sieve Analysis of Coarse and Fine Grained Aggregates" AASHTO T90, "Determining Plastic Limit and Plasticity Index of Soils"
PI and Gradation	$CBR = \frac{75}{1 + 0.728 \cdot P_{200} \cdot PI}$	P_{200} PI = product of percent passing the number 200 sieve and plasticity index	ASTM D6951, "Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications"
DCP*	$CBR = \frac{292}{DCP^{1.12}}$	DCP = dynamic cone penetrometer index, mm/blow	

Level 3 – Typical Values (Based on Calibration)

Level 3 is a less sophisticated approach and allows the user to use typical values of resilient modulus based on soil classification. Table 13.5 provides typical M_r values and a typical range of M_r values based on AASHTO and unified soil classification systems.

Table 13.5. Typical resilient modulus values for unbound granular and subgrade materials (modulus at optimum moisture content)**.**

Material Classification	M_r Range, psi	Typical M_r, psi
A-1-a	38,500-42,000	40,000
A-1-b	35,500-40,000	38,000
A-2-4	28,000-37,500	32,000
A-2-5	24,000-33,000	28,000
A-2-6	21,500-31,000	26,000
A-2-7	21,500-28,000	24,000
A-3	24,500-35,500	29,000
A-4	21,500-29,000	24,000
A-5	17,000-25,500	20,000
A-6	13,500-24,000	17,000
A-7-5	8,000-17,500	12,000
A-7-6	5,000-13,500	8,000
CH	5,000-13,500	8,000
MH	8,000-17,500	11,500
CL	13,000-24,000	17,000
ML	17,000-25,500	20,000
SW	28,000-37,500	32,000
SP	24,000-33,000	28,000
SW-SC	21,500-31,000	25,500
SW-SM	24,000-33,000	28,000
SP-SC	21,500-31,000	25,500
SP-SM	24,000-33,000	28,000
SC	21,500-28,000	24,000
SM	28,000-37,500	32,000
GW	39,500-42,000	41,000
GP	35,500-40,000	38,000
GW-GC	28,000-40,000	34,500
GW-GM	35,500-40,500	38,500
GP-GC	31,000-40,000	36,000
GC	24,000-37,500	31,000
GM	33,000-42,000	38,500

Enhanced Integrated Climatic Model

The enhanced integrated climatic model (EICM) considers the impact of changing moisture profiles in the pavement structure and subgrade over the design life of the pavement. The EICM is a one-dimensional coupled heat and moisture flow program which simulates changes in the behavior and characteristics of pavement and subgrade materials in conjunction with climatic conditions over several years of operation. It has three major components:

1. Climatic-Materials-Structural Model (CMS Model) developed by the University of Illinois
2. The CRREL Frost Heave and Thaw Settlement Model (CRREL) Model) developed at the United States Army Cold Regions Research and Engineering Laboratory (CRREL)
3. The Infiltration and Drainage Model (ID Model) developed at Texas A&M University.

Output of EICM is divided into internal output and external output. Internal output includes:
1. Values of saturation, S, which is Sequil unless oscillations in the groundwater table or cracks in the AC influence a moisture state change in the unbound aggregates base, unbound aggregates subbase or subgrade and unless freezing and thawing influence otherwise.
2. Unbound layer adjustment factor for unfrozen conditions, FU at each node.
3. FF signaled by calculation of freezing temperature calculations at respective node.
4. Thawing signaled by rise in temperature above freezing at respective node.
5. RR during the recovery period, which together with RF is used to compute the adjustment factor for recovering conditions, FR, at each node.

External output includes:
1. Unbound material MR adjustment factor as a function of position and time. Values of composite environmental effects adjustment factor, Fenv, are computed for every sublayer from the values of FF, FR, and FU at each node.
2. Fenv factors are sent forward to either the FEA or the LEA structural analysis modules where they are multiplied by MRopt to obtain MR as a function of position and time.
3. Temperatures at the surface and midpoint of each AC and UAB sublayer are statistically evaluated for incremental time periods during which damage is calculated.
4. Values of hourly temperature at the surface and set depth increments within the bound layers are calculated for thermal cracking.
5. Volumetric moisture content is reported for use in permanent deformation model for unbound aggregates base and unbound aggregates subbase.

13.4 Sensitivity of Mechanistic-Empirical Pavement Design Guide to Aggregate Properties

E* Master Curve

Viscoelastic, time and temperature dependent properties are dominated by properties of the asphalt binder. However, the filler effect on the rheology of the mastic must be considered. Equations [13-13] through [13-16] demonstrate that E* is dependent on the filler content of the mastic, expressed as the percent of aggregate smaller than 75 μm or percent passing the number 200 sieve, ρ_{200}. Other gradation factors such as ρ_4, $\rho_{3/8}$, $\rho_{3/4}$, V_a, and V_{beff} influence E* and also are impacted by aggregate gradation.

Resilient Moduli of Unbound Aggregates Base and Unbound Aggregates Subbase

The resilient modulus of the aggregates bases and subbases is considered to be stress dependent and when a FEA is used in MEPDG this stress dependency is accommodated by equation [13-18]. Although not definitively addressed in MEPDG, factors k_1, k_2, and k_3 are influenced by physical properties of the aggregate including shape and form, angularity, and surface texture. These properties impact the internal friction mobilized among aggregate particles which significantly impacts the level of resilient modulus under any condition or stress state or moisture state.

Research by the International Center for Aggregates Research (ICAR) has shown the importance of considering cross anisotropy in characterization of aggregate bases. ICAR has shown that in order to properly assess the structural integrity of layered systems, it is necessary to consider not only the vertical modulus but also the horizontal modulus as this substantially impacts the distribution of stresses within the pavement structure. Anisotropy is defined as the directional dependency of material properties. In other words, pavement systems are considered isotropic if the horizontal modulus equals the vertical modulus; alternatively, the material is considered to be anisotropic when the modulus values differ in different directions. An isotropic linear elastic material can be modeled with two elastic parameters; however, five material properties are required to characterize cross-anisotropic materials. Anisotropy in aggregate layers is more pronounced compared to asphalt and Portland Cement Concrete (PCC) layers. There are two major sources of anisotropy in pavement layers, which are defined as inherent anisotropy and load induced anisotropy. Inherent anisotropy is due to the preferred arrangement of aggregates particles upon compaction. As the compaction energy is applied on the layers, maximum dimensions of aggregate particles tend to align in the horizontal direction. Aggregates mixes with more flat and elongated particles show higher degrees of inherent anisotropy compared to mixes consisting of equiaxed particles. Materials with higher degree of anisotropy are more prone to shear-induced rutting in service. Inherent anisotropy or particle shape induced anisotropy is present even before the pavement is subjected to traffic loading as evidenced in Figure 13.4. Random geometry and arrangement of aggregates particles in compacted layers cause different stiffness properties in different directions. Additionally, the nature of the moving traffic load is another source of material anisotropy, also referred to as load-induced anisotropy.

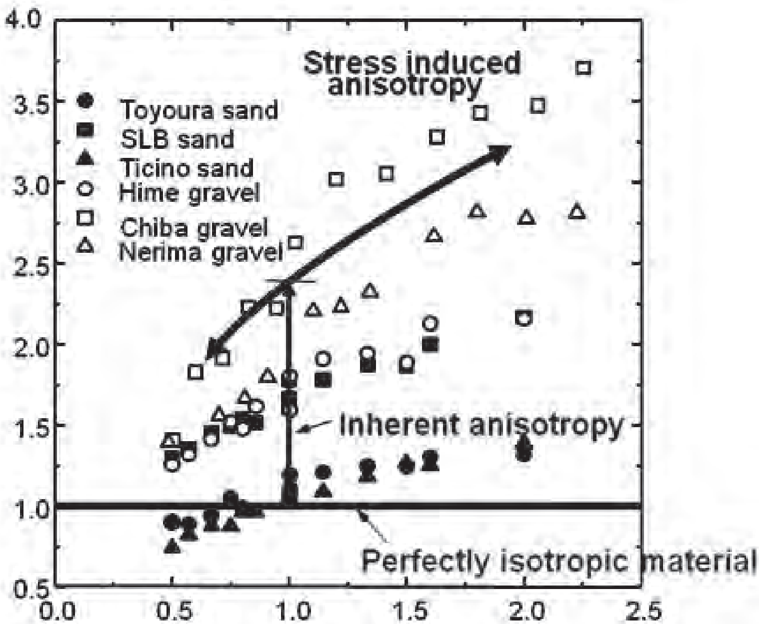

Figure 13.4 Impact of aggregate shape and form on level of anisotropy. (After Tatsuoka, 2000)**.**

ICAR research evaluated 246 data sets from the AASHTO Road Test which revealed that surface deflections calculated using isotropic material properties were smaller than the measured deflections under the Benkleman Beam. However, the accuracy of the calculated deflections improved when the aggregate base layer was considered to be anisotropic. Typically the level of anisotropy is characterized by the ratio of horizontal to vertical modulus (E_x/E_y). Analysis of the errors in the ICAR study showed that the error between measured and calculated responses were minimized when the stiffness in the horizontal direction assumed to be 30% of the stiffness in the vertical direction (E_x/E_y =0.3). Values of anisotropy, (E_x/E_y) of 0.4, 0.5 and 1 yielded progressively less accurate predictions.

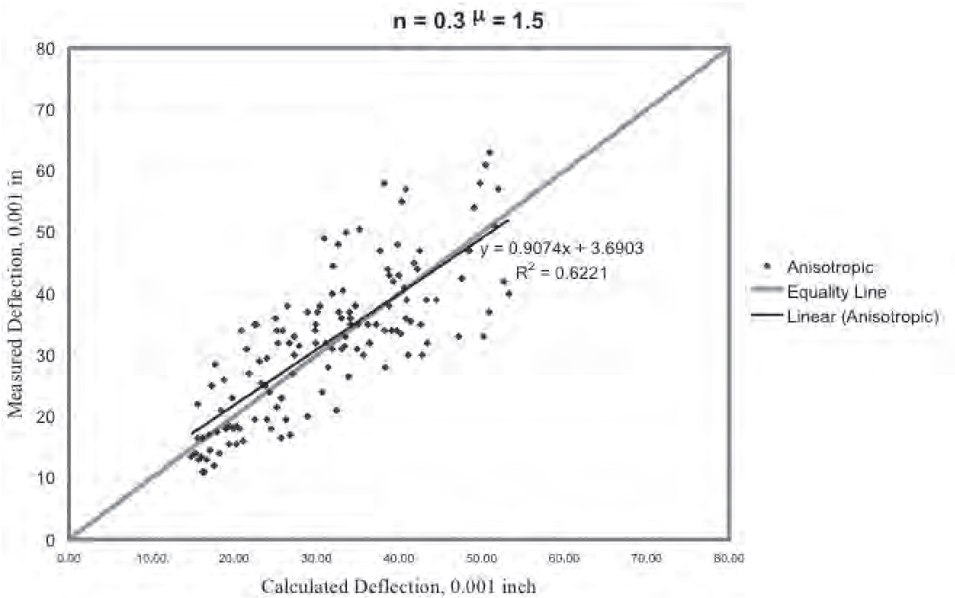

Figure 13.5 Measured v. calculated surface deflections from Loop 4 at AASHTO Road Test.

Figures 13.6 and 13.7 verify the importance of aggregates angularity, shape and textural properties on the level of cross anisotropy. Ashtiani (2009) showed clearly that increased angularity, a decrease in the quantity and degree of flat and elongated aggregates particles and an increase in surface texture all lead to lower anisotropy.

Lower levels of anisotropy or when there is a smaller difference between vertical and horizontal moduli, result in a more efficient distribution of stresses induced by traffic loading. Therefore, one would normally hope to produce aggregates with properties that minimize the degree of anisotropy.

The results presented in figures 13.6 and 13.7 clearly demonstrate the influence of aggregates shape features on the degree of anisotropy in unbound aggregates systems. Figure 13.6 shows the effect of aggregates texture and aggregates form on the level of anisotropy as characterized by the shear modular ratio (G_{xx}/G_{xy}). As evidenced in this plot, unbound aggregate systems with more cubical particles and rougher texture had higher shear modular ratios (G_{xx}/G_{xy}), and therefore had lower levels of anisotropy. In general, more isotropic materials produce a more favorable orthogonal load distribution when subjected to traffic loads.

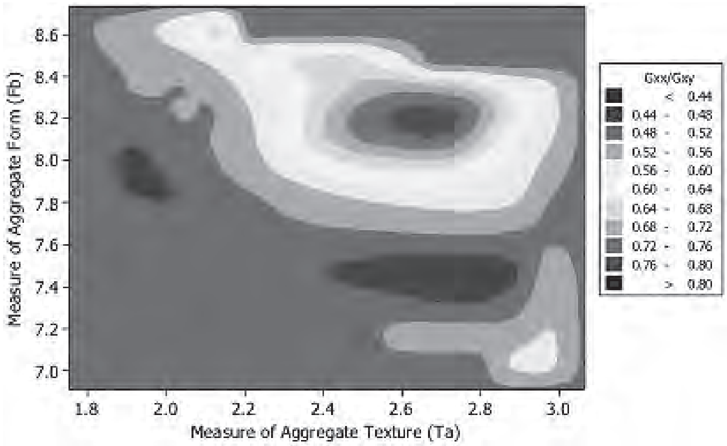

Figure 13.6 Increase in (G_{xx}/G_{xy}), the horizontal to vertical shear modulus as aggregate becomes more cubical (Fb increases) and aggregate becomes more textured (T_a increases). (After Ashtiani, 2009).

Figure 13.7 demonstrates the impact of particle texture and aggregate angularity on the level of anisotropy characterized by modular ratios (i.e., E_x/E_y). ICAR research showed that aggregate systems containing particles with rougher texture and more crushed surfaces (more angular) result in less anisotropic systems. Particle surface texture and angularity impact inter-particle frictional forces and therefore orthogonal load distribution capacity of the aggregate layer. Collectively, aggregate systems consisting of roughly textured and more angular particles result in systems that more efficiently distribute traffic loads and are less prone to rutting during service.

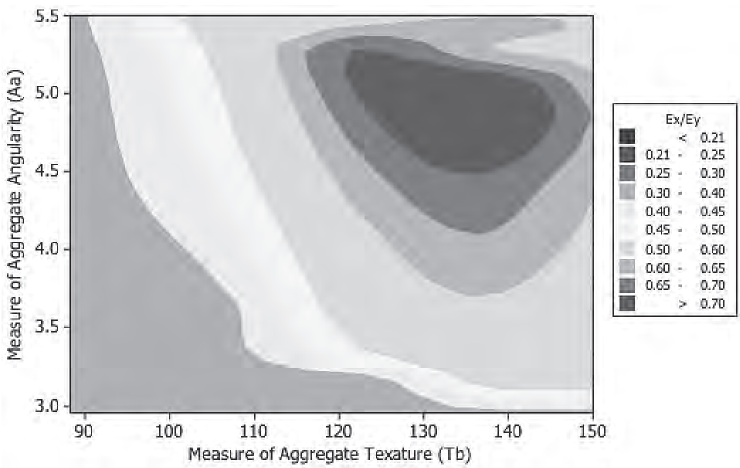

Figure 13.7 Increase in (E_x/E_y), the horizontal to vertical modulus as aggregate becomes more angular (A_a increases) and aggregate becomes more textured (T_b increases). (After Ashtiani, 2009).

Rutting Models for Asphalt Concrete and Aggregates Base and Subbase

The rutting model used for both the asphalt concrete and unbound aggregates base and subbase layers in MEPDG are of necessity rather simple and straightforward. The asphalt rutting model quantifies the ratio of plastic strain to total resilient strain in the asphalt sublayers as a function of temperature and number of loading cycles. It is not sensitive to aggregates properties in the asphalt mixture directly. However, since the E* is sensitive to aggregates properties (whether measured or calculated, equation [13-18]), and E* influences the value of total resilient strain calculated by either the LEA or FEA, aggregates properties are indirectly considered, equation [13-6].

In the unbound layers rutting is assess by means of equations [13-7] through [13-9]. Here aggregates properties influence the parameters β, ρ, and ε_0.

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Finn, F. N., Saraf, C. L., Kulkarni, R., Nair, K., Smith, W., and Abdullah, A. (1986), "Development of Pavement Structural Subsystems," NCHRP Report 291, Transportation Research Board.

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Appendix A
Engineering Properties of Soil and Aggregates Bases in MEPDG

Table A.1 Materials inputs required for unbound compacted materials for EICM calculations – Mass-Volume Parameters.

Material Property	Input Level	Description
Specific Gravity (oven-dry), G_S	1	A direct measurement using AASHTO T100 (performed in conjunction with consolidation tests – T180 for bases or T99 for other layers).
	2	Determine P_{200}* and PI** of the layer as below: 1. Determine P_{200} and PI. 2. Calculate G_S: $G_s = 0.041(PI)^{0.29} + 2.65$
	3	Not applicable.
Optimum gravimetric water content, W_{opts}, and maximum dry unit weight of solids, γ_{dmax}	1	Typically, AASHTO T180 compaction test for base layers and AASHTO T99 compaction test for other layers.
	2	Determine from D_{60}*, P_{200}* and PI** of the layer as illustrated below: 3. Read PI, P_{200}, and D_{60}. Identify the layer as a compacted base course, compacted subgrade, or natural in-situ subgrade. 4. Calculate S_{opt}: $S_{opt} = 6.752(P_{200} \cdot PI)^{0.147} = 78$ 5. Compute w_{opt}: If $P_{200} \cdot PI > 0$; $w_{opt} = 1.3\,(P_{200} \cdot PI)^{0.73} + 11$ If $P_{200} \cdot PI = 0$; $W_{opt\,(T99)} = 8.6425\,(D_{60})^{-0.1038}$ If layer is not a base course; $W_{opt} = w_{opt(T99)}$ If layer is a base course; $\Delta w_{opt} = 0.0156[w_{opt(T99)}]^2 - 0.1465_{wopt(T99)} + 0.9$ $W_{opt} = w_{opt(T99)} = \Delta w_{opt}$ 6. To obtain G_S refer to the level 2 procedure. 7. Compute $\gamma_{d\,max}$ for compacted materials, $\gamma_{d\,max\,comp}$ 8. $\gamma_{d\,max\,comp} = \frac{G_s\,\gamma_{d\,max}}{1 + \frac{W_{opt}\,G_s}{S_{opt}}}$ 9. Compute $\gamma_{d\,max\,comp}$ If layer is a computed material, $\gamma_{d\,max} = 0.9\,\gamma_{d\,max\,comp}$ If layer is a natural in-situ material, $\gamma_d = 0.90\,\gamma_{d\,max\,comp}$ 10. EICM uses γ_d for $\gamma_{d\,max}$
	3	Not applicable.

** P_{200} and D_{60} can be obtained from a grain-size distribution tests (AASHTO T27).*

*** PI can be determined from an Atterberg limit test (AASHTO T 90).*

Table A.2 Materials inputs required for unbound compacted material for EICM calculations – Saturated Hydraulic Conductivity, k_{sat}.

Material Property	Input Level	Description
Saturated hydraulic conductivity, k_{sat}	1	A direct measurement using a permeability tests (AASHTO T215) is recommended at this level.
	2	Determined from P_{200}*, D_{60}*, and PI** if the layer as below:: 1. Determine $P_{200}PI = P_{200} \cdot PI$. 2. If $0 < P_{200}PI < 1$ $k_{sat} = 118.11 \, x \, 10^{[-1.1275(\log D_{60}+2)^2+7.2816(\log D_{60}+2)-11.2891]}$ (ft/hr) Valid for $D_{60} < 0.75$ in If $D_{60} > 0.75$ in, set $D_{60} = -0.75$ mm 3. If $P_{200}PI > 1$ $k_{sat} = 118.11 \, x \, 10^{[0.0004(P_{200}PI)^2-0.0929(P_{200}PI)-6.56]}$ (ft/hr)
	3	Not applicable.

** P_{200} and D_{60} can be obtained from a grain-size distribution test (AASHTO T27).*

•• PI can be determined from an Atterberg limit test (AASHTO T90).

Table A.3 Materials inputs required for unbound compacted material for EICM calculations – Dry Thermal Conductivity (K) and Heat Capacity (Q).

<table>
<tr><th>Material Property</th><th>Input Level</th><th colspan="3">Description</th></tr>
<tr><td rowspan="15">Dry Thermal Conductivity, K</td><td>1</td><td colspan="3">A direct measurement is recommended at this level (ASTM E195).</td></tr>
<tr><td>2</td><td colspan="3">Not applicable.</td></tr>
<tr><td rowspan="13">3</td><td>Soil Type</td><td>Range</td><td>Recommended</td></tr>
<tr><td colspan="3">Btu/(ft)(hr)(0F)</td></tr>
<tr><td>A-1-a</td><td>0.22 – 0.44</td><td>0.30</td></tr>
<tr><td>A-1-b</td><td>0.22 – 0.44</td><td>0.27</td></tr>
<tr><td>A-2-4</td><td>0.22 – 0.24</td><td>0.23</td></tr>
<tr><td>A-2-5</td><td>0.22 – 0.24</td><td>0.23</td></tr>
<tr><td>A-2-6</td><td>0.20 – 0.23</td><td>0.22</td></tr>
<tr><td>A-2-7</td><td>0.16 – 0.23</td><td>0.20</td></tr>
<tr><td>A-3</td><td>0.25 – 0.40</td><td>0.30</td></tr>
<tr><td>A-4</td><td>0.17 – 0.23</td><td>0.22</td></tr>
<tr><td>A-5</td><td>0.17 – 0.23</td><td>0.19</td></tr>
<tr><td>A-6</td><td>0.16 – 0.22</td><td>0.18</td></tr>
<tr><td>A-7-5</td><td>0.09 – 0.17</td><td>0.13</td></tr>
<tr><td></td><td></td><td>A-7-6</td><td>0.09 – 0.17</td><td>0.12</td></tr>
<tr><td rowspan="3">Dry Heat Capacity, Q</td><td>1</td><td colspan="3">A direct measurement is recommended at this level (ASTM D2766).</td></tr>
<tr><td>2</td><td colspan="3">Not applicable.</td></tr>
<tr><td>3</td><td colspan="3">User selects design values based upon agency historical data or from typical values shown below:
• Typical values range from 0.17 to 0.20 Btu/(lb)(0F).</td></tr>
</table>

Table A.4 Options for estimating SWCC parameters.

Input Level	Procedure to Determine SWCC parameters	Required Testing
1	1. Direct measurement of suction (h) in psi, and volumetric water content (θ_w) pairs of values 2, Direct measurement of optimum gravimetric water content, w_{opt} and maximum dry unit weight $\gamma_{d\,max}$. 3. Direct measurement of the specific gravity of the solids, G_s. 4. Compute θ_{opt}. 5. Compute the S_{opt}. 6. Compute the θ_{sat}. 7. Based on a non-linear regression analysis, compute the SWCC model parameters af, b_f, c_f, and h_r using the equation proposed by Fredlund and Xing, and the (h, θ_w) pairs of values obtained in step 1. $$\theta_w = C(h)x\left[\frac{\theta_{sat}}{\left[ln\left[EXP(1)+\left(\frac{h}{a_f}\right)^{hf}\right]\right]^{cf}}\right]$$ $$C(h)=\left[1-\frac{ln\left(1+\frac{h}{h_r}\right)}{ln\left(1+\frac{1.45x10^5}{h_r}\right)}\right]$$ 8. Input a_f(psi), b_f, c_f, and h_r (psi) into the Design Guide software 9. EICM will generate the function at any water content (SWCC).	Pressure plate, filter paper, and/or Tempe cell testing. T180 or T99 for γ_d

Table A.4 Options for estimating SWCC parameters. (continued)

Input Level	Procedure to Determine SWCC parameters	Required Testing
2	1. Direct measurement of optimum gravimetric water content, W_{opt} and maximum dry unit weight γ max. 2. Direct measurement of the specific gravity of the solids, Gs. 3. The EICM will then internally do the following: a. Calculate $P_{200} \cdot PI$. b. Calculate θ_{opt} S_{opt}, and θ_{sat} as described for level 1. c. Based on a non-linear regression analysis, the EICM will compute the SWCC model parameters a_f, b_f, c_f, and h_r, by using correlations with $P_{200} \cdot PI$ and D_{60}. i. If $P_{200}PI > 0$ $a_f = \frac{0.003647(P_{200}PI)^{3.35} + 4(P_{200}PI) + 11}{6.895}$, psi $\frac{b_f}{c_f} + 2.313(P_{200}PI)^{.014} + 5$ $c_f = 0.0514(P_{200}PI)^{0.465} + 0.5$ $\frac{h_f}{a_f} = 32.44e^{0.0186(P_{200}PI)}$ ii. If $P_{200}PI = 0$ $a_f = \frac{0.8627(D_{60})^{-0.751}}{6.895}$, psi $b_f = 7.5$ $c_f = 0.17721n(D_{60}) + 0.7734$ $\frac{h_f}{a_f} = \frac{1}{D_{60} + 9.7e^{-4}}$ d. The SWCC will then be established internally using the Fredlund and Xing equation as shown for Level 1.	T180 or T99 for $\gamma_{d\ max}$. T100 for G_s. T27 for P_{200} and D_{60}. T90 for PI.
3	Direct measurement and input of P_{200}, PI, and D_{60}, after which EICM uses correlations with $P_{200}PI$ and D_{60} to automatically generate the SWCC parameters for each soil, as follows: 1. Identify the layer as a base course or other layer. 2. Compute G_s . 3. Compute $P_{200} \cdot PI$ 4. Compute S_{opt}, w_{opt}, and $\gamma_{d\ max}$ as shown for Level 2. 5. Based on a non-linear regression analysis, the EICM will compute the SWC model parameters a_f, b_f, c_f, and h_r by using correlations with $P_{200}PI$ and D_{60} as shown for Level 2. 6. The SWCC will then be internally established using the Fredlund and Xing equation as shown for Level 1	T27 for P_{200} and D_{60}. T90 for PI.

Table A.5 Summary of computations made by the EICM to determine adjustment factor for frozen material, F_F.

Step No.	Description
1	From user entered P_{200}, PI, and D_{60}, compute $P_{200} \cdot PI$.
2	Obtain an estimated value of M_{Ropt_est} (user input). M_{Ropt} is either a direct user input or can be estimated from other engineering properties such as CBR, R-value, structural layer coefficients (a_i), Penetration Index, or from gradation parameters.
3	Assign values for the Frozen Resilient Modulus, $M_{R\ frz}$: a. If $P_{200} \cdot PI = 0$ $M_{R\ frz} = 2.5 \times 10^6$ psi b. If $P_{200} \cdot PI > 0$ $M_{Rfrz} + 1 \times 10^6$ psi
4	Compute the frozen adjustment, factor FF: $F_F = \frac{M_{R\ frz}}{M_{R\ opt\_est}}$

Table A.6 Summary of computations made by the EICM to determine adjustment factor for recovering material, F_R.

Step No.	Description
1	Obtain user input gradation parameters P_{200}, P_4, PI, and D_{60} as well as estimated depth to water table, γ_{GWT}. Compute $P_{200} \cdot PI$.
2	Compute Recovery Ratio, RR: $RR = \frac{\Delta t}{T_R}$ where, Δt = number of hours elapsed since thawing started TR, the recovery period, is a function of the material properties: TR = 90 days for sand/gravels with $P_{200} \cdot PI < 0.1$ TR = 120 days for silts/clays with $0.1 < P_{200} \cdot PI < 10$; and, TR = 150 days for clays with $P_{200} \cdot PI > 10$.
3	Compute S_{opt}.

Table A.6 Summary of computations made by the EICM to determine adjustment factor for recovering material, F_R. (continued)

Step No.	Description
4	Compute S_{equil} from the SWCC: $$S_{equil} = C(h)x \frac{1}{\left[ln\left[EXP(1) + \left(\frac{h}{a_f}\right)^{hf}\right]\right]^{ef}}$$ $$C(h) = 1 - \frac{ln\left(1 + \frac{h}{h_r}\right)}{ln\left(1 + \frac{1.45x10^3}{h_r}\right)}$$ where h = $\gamma_{GWT} \cdot \gamma_{water}$, in psi a_f(psi), b_f, c_f, and h_r(psi).
5	Computer R_{equil} value as (5): $$\log R_{equil} = \log \frac{M_{R\,equil}}{M_{R\,opt}} = a + \frac{b-a}{1 + EXP\left[ln\left(-\frac{b}{a}\right) + k_m(S_{equil} - S_{opt})\right]}$$ Where a, b, and k_m are constants from table 2.3.8.
6	Compute the RF value as a function of PI, P_4, and P_{200}.

7	Compute the factor for recovering material, F_R:
	If (S_{equil} – S_{opt}) < 0:
	F_R = RF + R_{equil} * RR – RR * RF
	If (S_{equil} – S_{opt}) > 0:
	F_R = R_{equil} (RF + RR – RR*RF)

Table A.7 Recommended values of RF for coarse-grained materials (P_{200}<50%).

Distribution of Coarse Fraction*	P_{200} (%)	PI<12%	PI = 12% - 35%	PI>35%
Mostly Gravel P4<50%	<6	0.85	-	-
	6 – 12	0.65	0.70	0.75
	>12	0.60	0.65	0.70
Mostly Sand P4>50%	<6	0.75	-	-
	6 – 12	0.60	0.65	0.70
	>12	0.50	0.55	0.60
	50-85	0.5	0.55	0.60
	>85	0.40	0.50	0.55

** If it is unknown whether a coarse-grained material is mostly gravel or mostly sand, assume sand.*

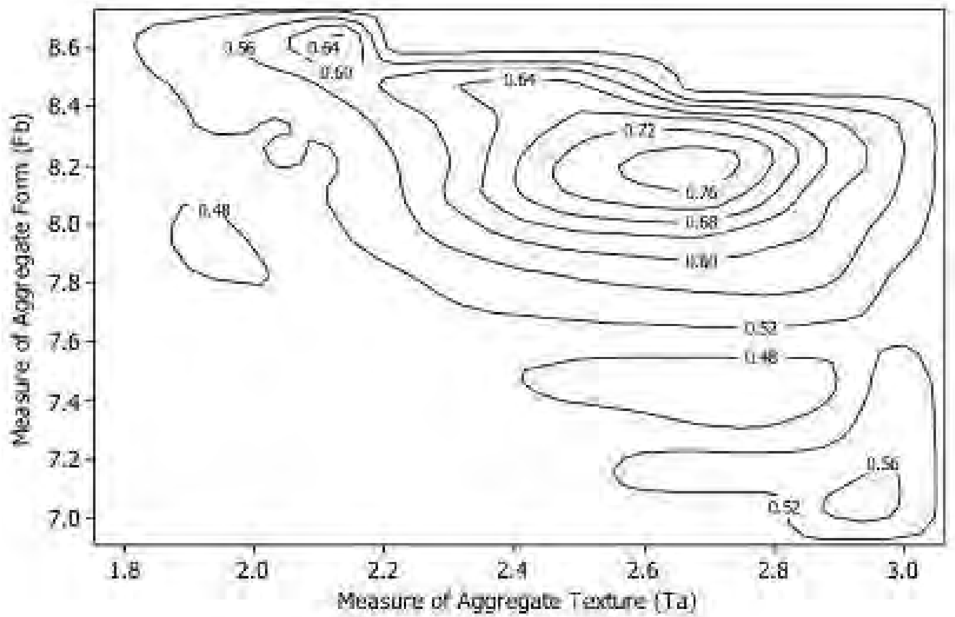


Figure. Impact of aggregate texture and form on anisotropy level assessed using modular Ratio (G_{xx}/G_{xy})

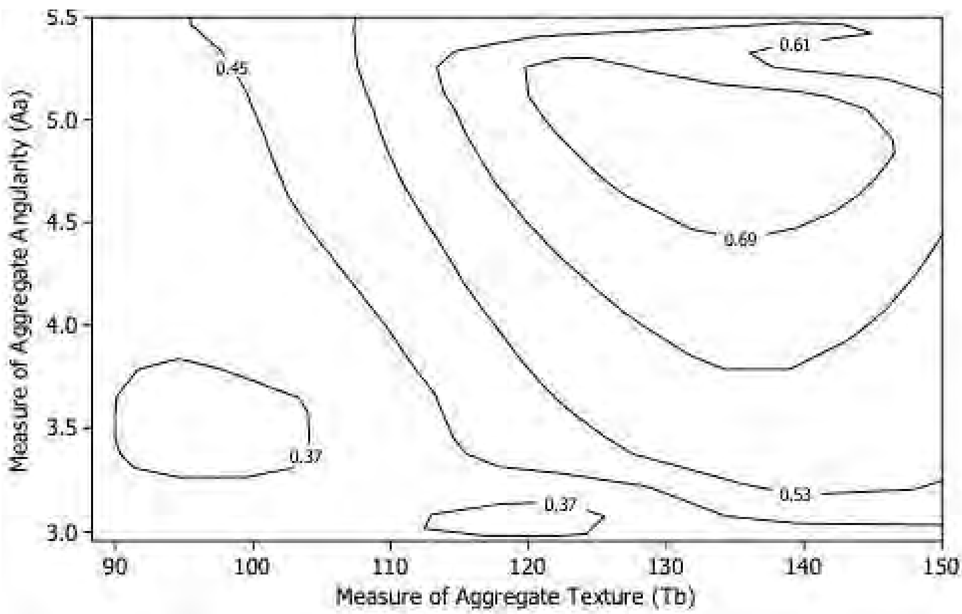


Figure. Impact of aggregate angularity and texture on anisotropy level assessed using modular ratio (E_x/E_y)

Chapter 14
Effect of Aggregates on the Characteristics and Performance of Portland Cement Concrete

David W. Fowler

First Edition
Thomas D. White

14.1 Introduction

Concrete is one of the most versatile and widely used construction materials in the world. From a simple walkway to a towering skyscraper, concrete can be molded into an infinite number of shapes and sizes lending it to many applications.

Concrete is a mixture of portland cement (or hydraulic cement), water, and coarse and fine aggregate. In very general terms, coarse aggregates are considered those aggregates particles that are retained on a No. 4 (9.5-mm) sieve and fine aggregates are those particles of aggregates that pass through the No. 4 (9.5-mm) sieve. Relative proportions of each of the basic constituents are shown in Table 14.1 for typical concrete mixtures. Other constituents are considered admixtures and/or supplementary products used for enhancement or control of certain concrete properties or characteristics.

Table 14.1 Range of Proportional Volumes of the Basic Constituents of Non-Air-Entrained Concrete (From Fig. 1-2, PCA, DCCM, EB001.14)

Cement	Water	Air	Fine Aggregates	Coarse Aggregates
7 - 15%	16 - 21%	1 - 3%	25 - 30%	31 - 51%

During the mixing process, the cement and water combine to make cement paste. This paste coats all the aggregates particles and, with the exception of a small percentage of entrapped air bubbles, fills all of the voids between the aggregates. For a short period of time after mixing, the concrete is in a "plastic" state. In this condition, the concrete is moldable and normally even flowable allowing it to be placed, consolidated and molded as desired.

A chemical reaction called hydration soon begins between the cement and water causing the paste to solidify and harden. Further detail is provided on hydration in Section 14.4. Through the hydration process, the cement paste becomes the "glue" or binder that coheres to the aggregates particles resulting in the solid composite material known as hardened concrete. Hydration will continue for years, even decades, as long as there is water available to react with the cement. In most instances, it is not necessary to depend on such long-term hydration. However, there usually is a needed period of days and even weeks for the hydration process to continue until the desired concrete properties are achieved. It is during this time that positive steps are usually needed to "cure" the concrete, that is, to inhibit evaporation of moisture from the concrete and to maintain sufficient moisture and temperature conditions within the concrete for this to occur (see Figure 14.1).

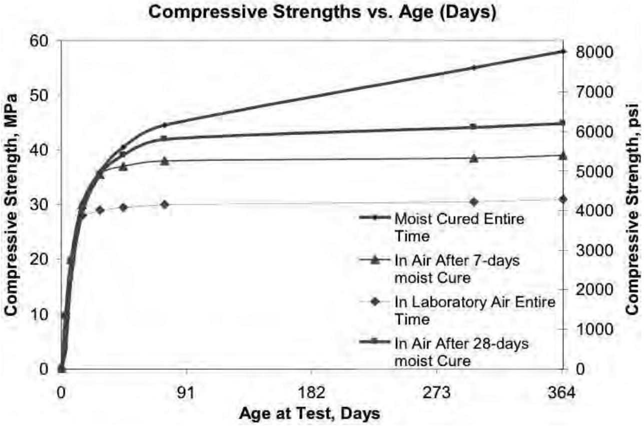


Figure 14.1 Effect of Curing on Compressive Strength
(From Figure 1-14, PCA DCCM, EB001.14)

A key relationship in concrete is the relative proportions between cement and water which is referred to as the water-cement ratio. Quite simply, it is the mass or weight of water per unit volume of concrete divided by the mass or weight of cement in the same unit volume. For example, a cubic yard of concrete with 300 pounds of water and 600 pounds of cement has a 0.50 water-cement ratio. Water-cement ratios for typical concrete mixtures range between 0.35 and 0.75 although specific needs may dictate a lower or higher ratio. This proportional relationship between water and cement dictates the properties of the cement paste. A lower amount of water in relation to cement means a higher concentration or density of cement particles in the paste. This in turn results in a higher density, lower permeability and higher strength in both the cement paste and concrete (see Figure 14.2).

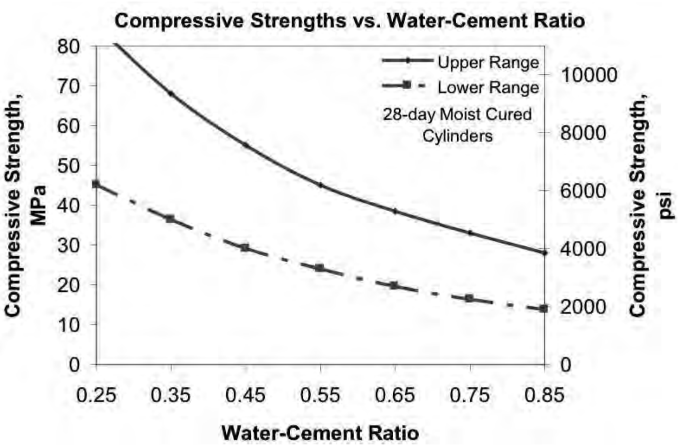


Figure 14.2 Typical Range of Relationships of Compressive Strength to Water-Cement Ratio
(From Figure 17-1, PCA DCCM, EB001.14)

14.2 Important Characteristics of Concrete

There are many characteristics of concrete that are important and even critical depending upon the situation. Though not all-inclusive, the characteristics discussed below are some of the more important ones. Note that much of the concrete produced today contains not only cement but also supplementary cementitious material which is further discussed in Section 14.5. Therefore, in the following discussions on concrete characteristics, the terms "water-cement ratio" and "cement hydration" can also mean "water-cementitious material ratio" and "cementitious material hydration." Aggregates play an important role in concrete properties and characteristics and will be highlighted in subsequent sections.

Workability

Workability is a broad term used to describe the plastic or fresh concrete's capacity to be transported, placed, consolidated and finished without the occurrence of segregation. Just as in other composite materials or as in aggregates with various particle sizes, there is always a potential for segregation in which the larger or heavier components separate from the smaller or lighter ones. Segregation in concrete easily can be observed during placement whereby a large portion of cement paste and mortar flows beyond the point of discharge while coarse aggregate particles quickly drop and settle near the point of discharge.

In general, workability is synonymous with the concrete's consistency needed for the process of transporting, placing, consolidating and finishing the concrete. For instance, concrete for large paving projects normally is transported in truck or trailer beds, dumped on the ground and then passed through a slipform paver (Figure 14.3, see color section) where it is augured, vibrated and extruded to its final shape.

At this point, the concrete needs to have a stiff consistency to avoid the potential of segregation during transport and placing; it also needs to hold its shape after extrusion. On the other hand, concrete that is transported in a mixer truck and then through a concrete pump where it is discharged into a heavily reinforced wall needs to have a more fluid consistency. The consistency of concrete is equated with the plastic concrete's ability to flow and is most commonly measured by slump. The slump test is described in Section 14.8.

Factors that affect workability include:

- Maximum size of coarse aggregates;
- Coarse and fine aggregates proportions, grading, particle shape and surface texture;
- Characteristics and amount of cement;
- Characteristics and amount of supplementary cementitious materials (see Section 14.5);
- Amount of entrained air (see Section 14.8);
- Amount of water;

- Characteristics and amount of admixtures (see Section 14.7);
- Concrete temperature; and
- Ambient temperature and humidity.

The International Center for Aggregate Research (ICAR) at The University of Texas at Austin has developed a rheometer that can measure the rheological properties for concrete with slumps greater than 3 inches (Fig. 14.4, see color section). The device measures the resisting torque at several different speeds to provide the yield stress on the vertical axis (analogous to the slump) and the viscosity as given by the slope of the line in the Bingham model for representing fresh concrete rheology (Fig. 14.5). The test requires about one minute to obtain the data to define the slope and intercept. The rheometer has been particularly useful for self-consolidating concrete and for concrete made with manufactured sand. The rheometer is commercially available as the ICAR rheometer.

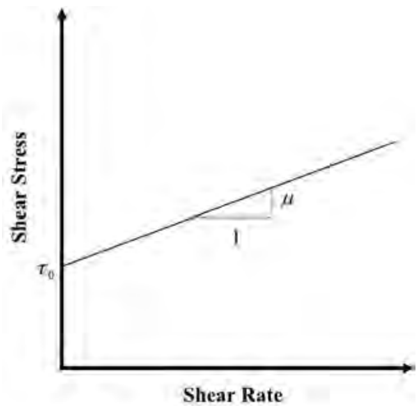


Figure 14.5 Bingham Model for Representing Fresh Concrete Rheology Durability

Durability refers to concrete's ability over time to adequately withstand the environmental conditions to which it is subjected. Among the more common detrimental conditions are freezing and thawing, deicers, chemical attack, sulfate attack, chloride intrusion and steel corrosion, delayed ettringite formation and alkali-aggregates reactivity. Damage from freezing and thawing occurs when moisture inside capillaries and pores in the cement paste and/or the aggregates freezes and turns to ice. In turning from a liquid to a solid, the water expands and creates excessive internal pressures. Deicing agents used during freeze-thaw conditions according to the Portland Cement Association (PCA) also can cause damage due to additional "osmotic and hydraulic pressures in excess of the normal hydraulic pressures produced when water in concrete freezes."

Deterioration of concrete can occur from exposure to certain chemicals such as acids. Sulfates from soil and groundwater can react with certain compounds in the cement paste forming expansive reaction products that internally damage the paste. Chlorides do not cause disintegration of concrete itself but intrusion of chloride ions can be the cause of corrosion of steel within concrete that in turn produces damaging internal pressures in the concrete. Alkali-aggregate reactivity is discussed in greater detail in Section 14.3 but, in general terms, constituents in some aggregates chemically react with alkalis in the concrete and potentially excessive expansion can occur.

Factors that affect durability include:
- Amount of entrained air (see Section 14.7)
- Cement type
- Water-cement ratio
- Degree of hydration (curing)
- Quality and permeability of the aggregates
- Bond between cement paste and aggregates

Strength

Strength is that property that determines structural capability, the ability to adequately carry or withstand applied loads. Because the hydration process continues over time, concrete strength increases over time. For practicality, concrete strength is measured and evaluated at a specified time, often 28 days from the time of placement. Compressive strength is the most commonly considered strength property. It is the measure of the maximum unconfined compressive stress the concrete resists before or at failure and is expressed in psi (MPa). Depending upon the application, other strength properties (tensile, shear, flexural, etc.) can be more important than compressive strength. For concrete pavements, flexural strength is the most critical structural property.

Interrelated to strength properties are the deflection characteristics of the concrete when subjected to loading. When subjected to a load or a force, the concrete will deflect and change shape to some degree in reaction to that force. Often referred to as stress-strain relationships, two common ones used in structural analysis are Modulus of Elasticity and Poisson's Ratio.

Another strength related characteristic is abrasion resistance. In many applications such as floors, decks, pavements, channels, and spillways, the concrete surface is subjected to abrading forces. The concrete must adequately resist or withstand the abrasive action to within acceptable limits of wear.

Factors that affect strength include:
- Amount of entrained air (see Section 14.7)
- Density and quality of the cement paste
- Water-cement ratio and degree of cement hydration (curing) (see Figure 14.2 and 14.3)
- Type and amount of supplementary cementitious materials (see Section 14.5)
- Strength of the aggregates
- Bond between cement paste and aggregates

Density (Unit Weight)

The term "density of concrete" is often thought of as the degree to which the concrete is consolidated. It is critical, in this sense, that concrete be adequately consolidated so that the large majority of entrapped air voids are expelled from the concrete. For the current discussion, however, the term "density" is the comparative unit weight or mass per unit volume of the concrete. For many concrete applications, this comparative density value by itself is not critical. Density values of normal weight concrete ordinarily range from 137 to 150 pounds per cubic foot (2195 to 2402 kg/m^3) depending on the type of aggregate used and the amount of entrained air in the concrete.

There are special applications, however, in which the density value is more critical. In order to reduce the dead load of a structure, structural members such as elevated slabs can be cast with lightweight aggregate concrete with densities ranging from 85 to 115 pounds per cubic foot (1362 to 1842 kg/m^3). Concrete used for radiation shielding, on the other hand, often requires the use of heavy weight aggregate to achieve densities from 180 to 380 pounds per cubic foot (2883 to 6087 kg/m^3).

Factors that affect density include:
- Amount of entrained air (see Section 14.7)
- Relative density of the aggregates
- Relative proportions of the various constituents

Permeability

Permeability is the degree to which a fluid can pass into and even through concrete. Specific situations or intended uses will dictate the degree of permeability that can be tolerated. Structures that are to be watertight such as reservoirs and tanks obviously need low permeability. Also, any conventional concrete that is to be durable must have a low permeability. There are special concrete uses that require a high permeability such as permeable pavements that are purposely to transfer surface water to underlying soil or a sub-surface drainage system.

Factors that affect permeability include:
- Water-cement ratio
- Degree of cement hydration (curing)
- Type and amount of supplementary cementitious materials
- Quality and permeability of the aggregates

Volume Stability

Hardened concrete will experience changes in volume when subjected to various changes in conditions. Volume changes (deflection and change in shape) due to externally applied loads or forces are discussed above in the section on *Strength*. This section addresses the common volume changes due to changes in temperature and moisture content.

Concrete will expand when there is a rise in temperature and it will contract when there is a drop in temperature. The amount of volume change is directly proportional to the amount of temperature change. This relationship is termed Coefficient of Thermal Expansion and is expressed as the unit length change per degree of temperature change.

The FHWA has delineated factors that affect thermal volume change characteristics of concrete which include:
- Type of aggregate (most significant factor)
- Cement content
- Water-cement ratio
- Concrete age
- Relative humidity

Concrete will slightly expand or swell with an increase in moisture content and will contract or shrink with a decrease in moisture content. The contraction that occurs due to the loss of moisture is commonly referred to as drying shrinkage. In practical terms, the potential amount of swell is always less than (about one fourth) the potential amount of shrinkage. Long term drying shrinkage, expressed in terms of change in unit length, usually ranges from 400 to 800 millionths.

Factors that affect moisture volume change characteristics include:
- Amount of mix water (most significant factor)
- Coarse aggregate size and amount
- Aggregate type
- Cement content
- Relative humidity

Appearance

More often than not there is some minimum level of acceptance regarding the outward appearance or "looks" of most concrete applications. Color, texture and finish as well as the uniformity of each of those are all facets of appearance. Whether it is a residential driveway or a retaining wall along a rural portion of interstate highway, there are certain expectations and requirements regarding appearance. Usually only some minimum amount of mottling, blemishes or discoloration is acceptable in the exposed surfaces of these applications.

On the other hand, there are those distinct applications in which looks or appearance of the concrete is one of the most critical characteristics. Such applications commonly fall into the categories of architectural and decorative concrete. These concretes may contain white cement or mineral pigment for a specific color. They may contain a round, smooth-surfaced gravel or a coarse aggregate of a particular color for an exposed aggregate finish. For the distinct look of terrazzo in which the concrete surface is ground and polished, a concrete could contain all special primary constituents (cement as well as fine and coarse aggregates) and color pigment. No matter what the source or uniqueness of the constituents, it is vital that uniformity and consistency be relatively constant in those constituents, in material handling and batching processes, and in the placing, finishing, and curing processes.

Factors that affect appearance include:
- Water-cement ratio
- Cement content, color and uniformity
- Supplementary cementing materials
- Coarse aggregate type, size, shape and amount
- Fine aggregate type and amount
- Admixtures (particularly calcium chloride)
- Variability in concrete proportions
- Forming materials
- Form release materials
- Placing and consolidation methods
- Finishing methods
- Curing materials and methods
- Post-curing surface treatments

14.3 The Role of Aggregates in Concrete

In the past, aggregate often was considered only as an inexpensive "filler" to occupy volume in concrete and offset the cost of the more expensive cement paste. Aggregates are indeed the largest portion of a typical portland cement concrete representing 60 to 75 percent of the total volume. However, aggregates are generally more chemically and dimensionally stable than cement paste and, as such, its role is much more than just a filler. Collectively, the aggregates particles form the internal structure that becomes bound in the cement paste. The inherent properties of the aggregates particles, the composite grading of the aggregate particles, and the bond between the aggregates particles and the cement paste are all critical to the characteristics and quality of the concrete.

Often, little thought has been given to the issues of aggregate quality in the more rudimentary uses of concrete. In these cases, there frequently has been a practice of using more cement to compensate for deficiencies of questionable or poor quality aggregates but not necessarily with overall success. More cement in a concrete mix may give needed strength and more cement paste may give needed workability but all this can lead to excessive volume change characteristics and increased costs. For overall quality and optimization of the various characteristics of concrete, strong consideration must be given to the aggregate components.

Sources of Aggregate for Concrete

Quarry rock as well as boulders, cobbles and larger pieces of gravel from naturally occurring deposits can be crushed and sized to produce coarse and fine aggregate. The individual aggregate particles produced from crushing are generally angular and rough textured. The fine aggregate resulting from crushing operations is termed manufactured sand.

Coarse and fine aggregate for concrete also can be derived from natural aggregate sources, such as glacial and river deposits, where the material needs little to no processing to meet particle size requirements. These materials are called sand and gravel, and their particles typically have round, smooth surfaces. Further discussion of the origin and characteristics of natural aggregate deposits is given in Chapter 3.

Important Properties of Aggregates in Portland Cement Concrete

The following sections describe the more important aggregates properties and characteristics that directly influence plastic and hardened concrete. Descriptions of the specific tests for these properties are presented in Chapter 2.

Maximum Particle Size

There is a physical issue relating to the maximum particle size of aggregates and that is its ability to adequately fit within the confines of the concrete section, in the spaces among the reinforcing bars, and between the outer reinforcing and the forms. For most situations, the maximum particle size of aggregates should not exceed the following criteria:

- One-fifth the narrowest dimension of a concrete member;
- Three-quarters the clear spacing between reinforcing bars and between the reinforcing bars and forms; and
- One-third the depth of slabs.

The maximum size of aggregates has a direct effect on the amount of cement paste needed to coat the aggregates particles. This is due to the distinct relationship between particle size and particle surface area. For a unit volume of aggregates, larger particles will have a lower total amount of surface area than smaller particles. Hence, concrete made with a larger maximum size of aggregate will require less cement paste for proper particle coating and less overall paste content for workability. A lower overall cement paste content results in less drying shrinkage.

Finally, the maximum particle size of aggregates can influence the strength of concrete. ACI 211.4R-93, *Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash*, states:

"For each concrete strength level, there is an optimum size for the coarse aggregate that will yield the greatest compressive strength per pound of cement. A 1 or ¾-in. (25 or 19-mm) nominal maximum-size aggregate is common for producing concrete strengths up to 9000 psi (62 MPa); and ½ or ⅜-in. (12.5 or 9.5-mm) above 9000 psi (62 MPa). In general, the smallest size aggregates produces the highest strength for a given *w/c+p* (water-cementitious materials ratio)."

Gradation

As defined in Chapter 2, gradation is the distribution of different particles of aggregates by size. This distribution of particle sizes is a key property in both the individual aggregates components in a concrete mix and the overall composite of the aggregates in that mix. Based on the simple fact that smaller particles can occupy space between larger particles, a more uniform distribution of different sized particles yields an aggregates structure with a lower amount of voids. A lower void content in the aggregates results in a lower needed volume of cement paste to fill those voids.

Coarse Aggregates

Coarse aggregates are defined in ASTM C 125-06a, *Standard Terminology Relating to Concrete and Concrete Aggregates*, as aggregate predominantly retained on the No. 4 (4.75-mm) sieve. ASTM C 33, *Standard Specification for Concrete Aggregates*, contains 14 different size designations for coarse aggregates. Although the largest nominal maximum size of the ASTM C 33 coarse aggregates designations is 3.5 inches (87.5-mm), coarse aggregates with maximum sizes to 6 inches (150-mm) have been successfully used. The C 33 designations are given both as a size number and as a nominal size. The nominal size is denoted by an upper and a lower sieve size which characterizes the general range of particle sizes in the coarse aggregates. The upper sieve is the largest sieve size on which *some* particles may be retained and the lower sieve is the largest sieve size on which *all* material may be retained. In general, at least 75 percent of the particles are retained between these two sieves. Table 14.2 shows the ASTM C 33 coarse aggregates sizes with the respective gradation limitations. Although the gradation sizes and limits of ASTM C 33 are commonly referenced, there are other agency specifications in successful use that contain other gradation criteria for coarse aggregates.

Fine Aggregate

ASTM C 125 states that fine aggregates are aggregates that completely passes the 9.5-mm (⅜-inch) sieve and almost entirely passes the 4.75-mm (No. 4) sieve and that is predominantly retained on the 75-μm (No. 200) sieve. Unlike coarse aggregates, ASTM C 33 contains only one general "size" of fine aggregates and the gradation limits are shown in Table 14.3.

Table 14.2 ASTM C 33 Coarse Aggregates Sizes (From Table 2, ASTM C 33 - 03)

Size Number	Nominal Size (Sieves with Square Openings)	Amounts Finer than Each Laboratory Sieve (Square-Openings), Mass Percent													
		100 mm (4 in)	90 mm (3½ in)	75 mm (3 in)	63 mm (2½ in)	50 mm (2 in)	37.5 mm (1½ in)	25.0 mm (1 in)	19.0 mm (¾ in)	12.5 mm (½ in)	9.5 mm (⅜ in)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No.16)	300 µm (No.50)
1	90 to 37.5 mm (3½ to 1½ in.)	100	90 to 100	—	25 to 60	—	0 to 15	—	0 to 5	—	—	—	—	—	—
2	63 to 37.5 mm (2½ to 1½ in.)	—	—	100	90 to 100	35 to 70	0 to 15	—	0 to 5	—	—	—	—	—	—
3	50 to 25.0 mm (2 to 1 in.)	—	—	—	100	90 to 100	35 to 70	0 to 15	—	0 to 5	—	—	—	—	—
357	50 to 4.75 mm (2 in. to No. 4)	—	—	—	100	95 to 100	—	35 to 70	—	10 to 30	—	0 to 5	—	—	—
4	37.5 to 19 mm (1½ to ¾ in.)	—	—	—	—	100	90 to 100	20 to 55	0 to 15	—	0 to 5	—	—	—	—
467	37.5 to 4.75 mm (1½ in. to No.4)	—	—	—	—	100	95 to 100	—	35 to 70	—	10 to 30	0 to 5	—	—	—
5	25.0 to 12.5 mm (1 to ½ in.)	—	—	—	—	—	100	90 to 100	20 to 55	0 to 10	0 to 5	—	—	—	—
56	25.0 to 9.5 mm (1 to ⅜ in.)	—	—	—	—	—	100	90 to 100	40 to 85	10 to 40	0 to 15	0 to 5	—	—	—
57	25.0 to 4.75 mm (1 in. to No. 4)	—	—	—	—	—	100	95 to 100	—	25 to 60	—	0 to 10	0 to 5	—	—
6	19.0 to 9.5 mm (¾ to ⅜ in.)	—	—	—	—	—	—	100	90 to 100	20 to 55	0 to 15	0 to 5	—	—	—
67	19.0 to 4.75 mm (¾ in to No. 4)	—	—	—	—	—	—	100	90 to 100	—	20 to 55	0 to 10	0 to 5	—	—
7	12.5 to 4.75 mm (½ in. to No.4)	—	—	—	—	—	—	—	100	90 to 100	40 to 70	0 to 15	0 to 5	—	—
8	9.5 to 2.36 mm (⅜ in. to No. 8)	—	—	—	—	—	—	—	—	100	85 to 100	10 to 30	0 to 10	0 to 5	—
89	9.5 to 1.18 mm (⅜ in. to No.16)	—	—	—	—	—	—	—	—	100	90 to 100	20 to 55	5 to 30	0 to 10	0 to 5
9 *	4.75 to 1.18 mm (No. 4 to No.16)	—	—	—	—	—	—	—	—	—	100	85 to 100	10 to 40	0 to 10	0 to 5

** Size number 9 aggregates are defined in Terminology C 125 as fine aggregates. It is included as coarse aggregates when it is combined with a size number 8 material to create a size number 89, which is a coarse aggregate as defined by Terminology C 125.*

Table 14.3 ASTM C 33 Fine Aggregates Grading Limits (From Section 6.1, ASTM C 33 – 03)

Sieve Size		Percent Passing
9.5-mm	(⅜-in.)	100
4.75-mm	(No. 4)	95-100
2.36-mm	(No. 8)	80-100
1.18-mm	(No. 16)	50-85
600-mm	(No. 30)	25-60
300-mm	(No. 50)	5-30
150-mm	(No. 100)	0-10

ASTM C 33 has two additional restrictions related to fine aggregates that limit extremes in gradation and assure more uniform grading throughout the various particle sizes:

- No more than 45 percent of the aggregate shall pass any sieve and be retained on the next consecutive sieve; and
- The fineness modulus shall be not less than 2.3 nor more than 3.1.

Although it can be applied to any size aggregates, fineness modulus (FM) is most commonly associated with fine aggregates as an indication of the fineness of the material. It is determined from the gradation results and calculated as the summation of the cumulative percentage amounts of retained material for a given set of sieves divided by 100. The applicable sieve set for a fine aggregates are the ASTM C 33 standard sieves. Table 14.4 shows examples of fineness modulus of fine aggregates with gradings at the upper and lower limits of ASTM C 33. As demonstrated in the table, higher values of FM indicate a coarser material. The table also demonstrates that gradings at the ASTM C 33 limits throughout the sieve set exceed the allowable limits on fineness modulus.

Table 14.4 Examples of Fineness Modulus for Fine Aggregates with Gradations at the ASTM C 33 Upper and Lower Limits

		Very Fine Grading		Very Coarse Grading	
Sieve Size		Cumulative Percent Passing	Cumulative Percent Retained	Cumulative Percent Passing	Cumulative Percent Retained
⅜ in.	(9.5 mm)	100	0	100	0
No. 4	(4.75 mm)	100	0	95	5
No. 8	(2.36 mm)	100	0	80	20
No. 16	(1.18 mm)	85	15	50	50
No. 30	(600 μm)	60	40	25	75
No. 50	(300 μm)	30	70	5	95
No. 100	(150 μm)	10	90	0	100
Fineness Modulus			**2.15**		**3.45**

The gradation limits of ASTM C 33 are relatively wide and, depending upon the type and application of the concrete, a different grading may be warranted. For example, greater amounts of material passing the No. 50 (300-μm) sieve increase workability, increase ease of pumping, reduce bleed rate and ease the hand finishing of concrete. Bleeding is the migration of some of the mix water to the concrete surface after placement, consolidation and leveling or strike-off of the plastic concrete. It is due to the settling of aggregates and cement while the concrete is still in a plastic state. For concrete that is to be hand placed and more specifically hand finished, more than 15 percent of the material should pass the No. 50 (300-μm) sieve. In this same light, ACI 304.2R-96, *Placing Concrete by Pumping Methods*, recommends that the ASTM C 33 gradation limits for fine aggregate be amended as shown in Table 14.5 for concrete that is to be pumped.

Table 14.5 ACI 304.2R Recommended Amendments to ASTM C 33 Fine Aggregate Grading Limits for Pumped Concrete

Sieve Size		Percent Passing
No. 50	(300-μm)	15 – 30
No. 100	(150-μm)	5 – 10

Microfines

A more recent term related to aggregates particle size is microfines. This term refers to the material that passes the No. 200 (75-μm) sieve. In soils engineering terminology, material passing a No. 200 (75-μm) sieve classifies as silt and/or clay depending on its plasiticity characteristics. This minus No. 200 (75-μm) size material is generally considered deleterious to concrete because of its propensity to coat aggregates particles and hinder the bond with cement paste. For concrete containing a sufficient quantity of microfines that are more clay-like, there can be significant demand for increased water to achieve adequate workability.

ASTM C 33 places limits on the amount of microfines. For coarse aggregates, the maximum allowable amount is 1.0 percent. An increase to 1.5 percent is allowed if the material is free of clay and shale. An increase is also allowed if the fine aggregates contains less than the specified maximum amount.

For natural sand, the ASTM C 33 limits are 3 percent for concrete subject to abrasion and 5 percent for all other concrete. For manufactured fine aggregates, the allowable limits are increased to 5 percent when abrasion is involved and 7 percent for all other applications. It should be noted, however, that ICAR research has shown that concrete made with manufactured aggregates microfines nearly always has less abrasion loss than concrete made with good quality natural sand. Since manufactured fine aggregates usually has between 10 and 20 percent microfines, this material requires further processing, usually washing of the aggregates, to satisfy these limits. Extensive research at ICAR has shown that good quality concrete can be made with high microfine contents (up to 17 percent of the sand content) for nearly any microfines free from clay. Generally compressive strengths are about the same, flexural strengths are somewhat higher, abrasion loss is less and the coulombs passed in the rapid chloride permeability test are usually less. Workability can be the same as for natural sand concrete when high range water reducers are used.

Composite Gradation

It was determined long ago that the critical grading of aggregates in a concrete mix is that of the composite of all of the aggregates constituents in the mix. Quoting one of the statements made on this issue from the often cited 1918 research document by Duff Abrams, *Design of Concrete Mixtures*:

> "There is an intimate relation between the grading of the aggregates and the quantity of water required to produce a workable concrete."

The required quantity of water correlates directly to a required quantity of cement paste. It is cement paste that fills voids between the aggregates and it is the overall aggregates grading that has the greatest influence on the amount of void space.

It should be noted that absolute minimum void space between aggregates does not necessarily translate into concrete with all optimum properties. As related to strength for example:

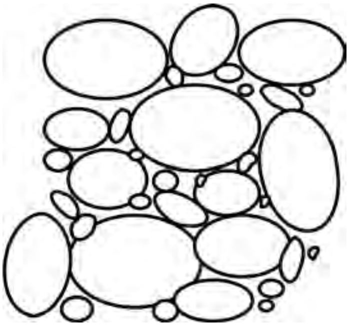
> "The aggregates grading which produces the strongest concrete is not that giving the maximum density (lowest voids). A grading coarser than that giving maximum density is necessary for highest concrete strength. The richer the mix, the coarser the grading should be for an aggregates of given maximum size; hence, the greater the discrepancy between maximum density and best grading."

A concrete's abrasion resistance is affected in the same way. The coarser the grading of the aggregates, up to certain limits, the lower the wear. Thus, a balanced view is needed toward composite aggregates gradation. The benefits of better volume change characteristics that come from lower water content should be balanced with the need for adequate paste content to achieve other concrete properties.

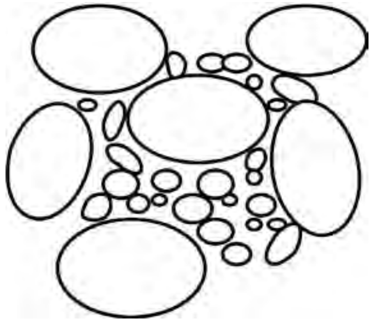
Well-Graded Aggregates

Well-graded aggregates have a uniform distribution of the various sized particles. This is graphically represented in the schematic of Figure 14.6. Well-graded aggregates are normally desired for concrete because not only is less paste required but the tendency for segregation while the concrete is plastic is less due to the balance of particle sizes and the more stable aggregates structure.

With gap graded aggregates, there is a "gap" in the particle size distribution, a range of aggregates sizes in which there is either a low amount of particles or an absence of those particles. This is illustrated in Figure 14.6. For normal concrete mixtures, gap-graded aggregates have a greater amount of voids between aggregates particles and the aggregates structure is less stable in the plastic concrete. Hence, there is a higher demand for water and cement paste and there is a greater tendency in the plastic concrete for segregation. There are applications, however, when a gap-graded aggregate is desired such as for pervious concrete bases and pavements. In these applications, the amount of paste is purposely reduced so that the bulk of the voids are not filled. Further discussion on pervious concrete is contained in Section 14.9.



Example of a Well-Graded Aggregates



Example of a Gap-Graded Aggregates

Figure 14.6 Example of a Well-Graded Aggregates and Gap-Graded Aggregates

Surface Texture

A rough-textured surface on aggregates have a greater surface area than a smooth surface and requires some increase in water to produce the same degree of workability in concrete, although water reducing admixtures can be used to reduce the amount of water required. The rougher texture, however, creates a better bond with cement paste. This has little effect on compressive strength for typical or normal strength concrete mixtures but does provide better flexural strength for all concrete and higher achievable compressive strength for high-strength concretes.

Particle Shape

Angular aggregates as well flat and elongated aggregates particles have a greater surface area and create greater void space as compared to rounded aggregates. Angular aggregates and flat and elongated aggregates require more water to produce workable concrete; however, water reducing admixtures can be used to minimize the amount of water required to achieve a needed level of workability.

Bulk Density (Unit Weight)

Bulk density, often referred to as unit weight, is the mass per unit volume of an aggregates at some level or degree of compaction. This volume is occupied by both aggregates particles and the voids between the aggregates particles. Measurement of bulk density can be made on fine aggregates, coarse aggregates and on aggregates composites in loose and/or compacted states. These can be useful in evaluating various compositions for level of density and void content. The compacted bulk density of coarse aggregates is often used in the determination of the amount or proportion of coarse aggregates in a concrete mixture.

Relative Density (Specific Gravity)

The relative density or specific gravity of aggregates has a direct effect on the bulk density or unit weight of concrete. This is critical for those applications that have defined requirements on concrete weight. In these instances, the weight parameters will dictate the selection of the aggregates. Concrete made with normal weight aggregates can have bulk densities form 130 to 155 pcf (2082 to 2483 kg/m^3). Lightweight concrete of 85 to 115 pcf (1362 to 1842 kg/m^3) bulk density can often be required due to structural design limitations. Conversely, high density or heavyweight concrete such as for radiation shielding can require a bulk density of the concrete up to 400 pcf (6407 kg/m^3).

Aggregates relative density values are often utilized in concrete proportioning and are used in yield computations of concrete batches. For concrete mixtures proportioned on the basis of aggregate in a dry condition, the bulk (or bulk dry) relative density values are used. Bulk saturated, surface dry (SSD) relative density values are employed when aggregates is considered in its SSD condition.

Aggregates with comparatively uniform relative density produces uniform concrete mixtures. However, mixtures of aggregates having markedly different relative density values tend to segregate during handling and mixing procedures. These mixtures create a variable demand for water and require constant monitoring.

Absorption/Pore Structure

Aggregates contain some volume of pores that are open at the aggregates surface and have the capacity to absorb water. If these pores are interconnected beneath the surface, absorption of water can be significant. Aggregates with more connected pores and rougher surface texture retain a significant amount of moisture.

The moisture condition of the aggregates surface and pores at the time of batching and mixing of the concrete and the variability in moisture condition from batch to batch is crucial to the characteristics of concrete. If the aggregates pores are not completely filled with water, a portion of batch water will be absorbed into the pores to bring the moisture condition to equilibrium. This decreases workability of the concrete and lowers the water-cement ratio. If the aggregates pores are completely filled and there is additional moisture on the surface of the aggregates, that surface water is in excess of the equilibrium moisture condition and will become part of the batch water. This increases workability and raises the water-cement ratio. To produce consistent quality concrete, the aggregates moisture conditions must be monitored and the batch water must be appropriately adjusted to compensate for the deficiency from or the excess beyond the equilibrium or SSD condition. See Figure 14.7

Figure 14.7 Aggregates Moisture Conditions (From Figure 5-12, PCA DCCM, EB001.14)

Aggregates with high absorption many times are more susceptible to problems from freeze-thaw and wetting and drying. Some may shrink on drying. Table 14.6 from the America Concrete Association (ACI) shows drying shrinkage values of concrete made with aggregates of varying absorption.

Table 14.6 Drying Shrinkage of Concrete with Various Aggregates
(From Table 2.1, ACI 221R – 96)

Aggregates	Specific gravity	Absorption, percent	One-year shrinkage, 50 percent relative humidity, millionths	One-year shrinkage, percent
Sandstone	2.47	5	1160	0.12
Slate	2.75	1.2	680	0.07
Granite	2.67	0.5	470	0.05
Limestone	2.74	0.2	410	0.04
Quartz	2.65	0.3	320	0.03

Freeze-Thaw Durability

As discussed earlier, excessive internal pressures can be created inside confined, saturated pores when the absorbed water freezes and turns to ice. An aggregates particle's ability to resist freeze-thaw damage is dependent upon the particle's size and its internal pore structure and pore sizes. These, in turn, determine how easily pores can become saturated.

An important aggregates performance problem is "D" cracking which occurs when certain frost-susceptible aggregates are used in concrete pavements. Moisture accumulates in locations such as the bottom of pavement slabs close to joints, cracks and edges of the pavement. Subsequent freezing and thawing cycles cause the aggregate and the concrete to crack and deteriorate. At these critical locations, the pavement concrete disintegrates from the bottom of the slab upward toward the surface. Cracks parallel to the edge of the slab eventually appear at the pavement surface which is a distinguishing feature of "D" cracking.

A lesser durability problem is popouts. A popout occurs when a frost-susceptible aggregates near the concrete surface becomes saturated and experiences freezing and thawing. The resultant expansive pressures crack the aggregates and the surrounding mortar in a cone shaped fracture causing the fragment to come loose from the surface.

As stated in Chapter 2, the Sulfate Soundness Test of ASTM C 88 is intended to provide an estimate of the ability of aggregates to resist the weathering action that occurs in concrete. For fine aggregates, the ASTM C 33 maximum allowable loss of material in the test is 10 percent for a sodium sulfate solution and 15 percent for a magnesium sulfate solution. Table 14.11 shows the acceptable maximum loss values for coarse aggregates. For both fine and coarse aggregates, ASTM C 33 provides further acceptance criteria for material not meeting the soundness loss requirements.

Wetting and Drying Properties

Damage from wetting and drying is normally not as significant as with freezing and thawing but in the same manner, an aggregates particle's ability to resist damage is dependent upon the pore structure of the aggregates. Certain aggregates experience greater volume changes due to changes in moisture content. With some aggregates, cycles of wetting and drying can potentially cause the development of severe strain in the aggregates. There can be differential swelling of certain individual aggregates particles such as clay balls and shales that develop significant enough pressures to fracture the surrounding paste and cause popouts. Even if excessive pressures do not develop, these same types of friable particles can become weakened upon wetting and, with repeated wetting and drying, may degrade.

Thermal Properties

Since aggregates are the largest constituent of concrete, it has a direct effect on concrete's thermal properties. The coefficient of thermal expansion is the unit length change for degree temperature change. Table 14.7 contains typical values for coefficient of thermal expansion for various types of aggregate and for cement paste. Table 14.8 shows some typical values of Coefficient of Thermal Expansion for concretes made with various aggregates types. The data in the two tables are from separate research but comparison of the two shows the general relationship between aggregates and concrete thermal expansion characteristics. In broad terms, concrete made with sandstone or quartzite will have nearly twice the thermal movement as that made with limestone for the equivalent change in temperature.

Table 14.7 Typical Coefficient of Thermal Expansion (CTE) Values for Various Aggregates and Cement Paste (From FHWA Publication No. HIF-07-004 Table 3-11)

	Coefficient of Thermal Expansion	
	10^{-6} / °C	10^{-6} / °F
Aggregates		
Granite	7 to 9	4 to 5
Basalt	6 to 8	3.3 to 4.4
Limestone	6	3.3
Dolomite	7 to 10	4 to 5
Sandstone	11 to 12	6.1 to 6.7
Quartzite	11 to 13	6.1 to 7.2
Marble	4 to 7	2.2 to 4
Cement Paste		
w/c = 0.4	18 to 20	10 to 11
w/c = 0.5	18 to 20	10 to 11
w/c = 0.6	18 to 20	10 to 11

Table 14.8 Effect of Aggregates Type on Thermal Coefficient of Expansion of Concrete. (From PCA, DCCM, EB001.14, Table 15-1)

Aggregates Type (from one (1) Source)	**Coefficient of Expansion,** Millionths per °C	**Coefficient of Expansion,** Millionths per °F
Quartz	11.9	6.6
Sandstone	11.7	6.5
Gravel	10.8	6.0
Granite	9.5	5.3
Basalt	8.6	4.8
Limestone	6.8	3.8

Note: Coefficients of concretes made with aggregates from different sources may vary widely from these values, especially those for gravels, granites and limestones (Davis 1930).

The coefficient of thermal conductivity is a measure of the rate at which heat is transmitted through the mass of a material. Major factors affecting the thermal conductivity of concrete are the density of the concrete (which is directly influenced by the relative density of the aggregates), the type of aggregates and moisture in the concrete. Table 14.9 provides illustration of this.

Table 14.9 Practical Thermal Conductivity Values for Concrete (From Table 2.4, ACI 122R – 02)

Aggregates Type	**Internal Relative Humidity, %**	**Thermal Conductivity†, Btu/hr·ft² (°F/in.)**			
		Concrete Density‡, lbs/ft³			
		120	**130**	**140**	**150**
Limestone	60	—	9.4	11.1	13.8
	80	—	10.0	11.7	13.75
Sand gravel, > 50% quartz or quartzite	60	—	11.0	15.3	20.5
	80	—	11.8	16.5	22.0
Sanded expanded and sintered clay, shale, slate, fly ash; sanded pumice, scoria, cinders	60	9.1	—	—	—
	80	9.9	—	—	—

†Multiply table values by 0.1442 to convert to W/m·K; ‡Multiply table values by 16 to convert to kg/m³

Fire Resistance

Fire resistance of structural concrete is its ability to provide protection from the fire and to maintain structural capability. Aggregates thermal conductivity and volume expansion are two characteristics that are important with respect to fire resistance. Lightweight aggregates, which have more and larger pores than conventional aggregates, have relatively low thermal conductivity and hence provide a more fire-resistant concrete. Since aggregates usually have a lower coefficient of expansion than mortar, most aggregates help resist concrete expansion. However, some aggregates, such as granite, undergo rapid expansion at high, critical temperatures. The severe spalling and popouts that result can lead to distress and structural failure. At high temperatures dolomite calcines. A coating of calcine is a good insulator and protects the underlying concrete.

In general, normal weight concrete made with carbonate aggregates has somewhat better fire resistance than that made with siliceous aggregates. As an example, siliceous aggregates concrete expands almost 20 percent more than carbonate aggregates concrete at an elevated temperature of 1112 ºF (600 ºC). The same holds true for structural capacity. A simply supported concrete slab with a 1-inch (25-mm) distance from center of tension reinforcing bars to the fire-exposed surface will have three hours of fire endurance for carbonate aggregates concrete as compared to two hours for siliceous aggregates concrete.

Deleterious Materials

Materials may be present in aggregates sources that have an undesirable effect on concrete. Chemicals present in soils at a construction site may react with the concrete. Organic material, mica, iron oxide, lightweight chert, shale, coal, lignite and alkali reactive aggregates are potential deleterious materials that can cause harmful reactions with concrete. ASTM C 33 limits for deleterious material for fine aggregates are shown in Table 14.10 and in Table 14.11 for coarse aggregates. For coarse aggregates, acceptable limits vary depending upon the application of the concrete and the weathering conditions the concrete will be subjected.

Table 14.10 ASTM C 33 Limits for Deleterious Substances in Fine Aggregates (From Table 1, ASTM C 33 – 03)

Item	Mass Percent of total Sample, max
Clay lumps and friable particles	3.0
Material finer than 75-um (No. 200) sieve:	
Concrete subject to abrasion	3.0*
All other concrete	5.0*
Coal and lignite:	
Where surface appearance of concrete is of importance	0.5
All other concrete	1.0

** In the case of manufactured sand, if the material finer that 75-um (No. 200) sieve consists of the dust of fracture, essentially free of clay or shale, these limits are permitted to be increased to 5 and 7%, respectively.*

Organic Impurities

Organic material can affect the cement hydration process and therefore the strength and durability of concrete. Natural sands can contain organic material and ASTM C 33 requires that fine aggregate be evaluated using a colorimetric test, ASTM C 40, to determine the presence of "injurious" organic impurities. If such impurities are detected, the fine aggregate can be further tested in accordance with ASTM C 87 to determine the effect on the compressive strength of mortar. If the strength is 95 percent or greater of a control sample, the sand is acceptable for use.

Table 14.11 ASTM C 33 Limits for Deleterious Substances and Physical Property Requirements of Coarse Aggregates (From Table 3, ASTM C 33 – 03)

NOTE 1 - See Fig. 1 for the location of the weathering regions and Note 9 for guidance in using the map. The weathering regions are defined as follows:
(S) Severe Weathering Region - A cold climate where concrete is exposed to deicing chemicals or other aggressive agents, or where concrete may become saturated by continued contact with moisture or free water prior to repeated freezing and thawing.
(M) Moderate Weathering Region - A climate where occasional freezing is expected, but where concrete in outdoor service will not be continually exposed to freezing and thawing in the presence of moisture or to deicing chemicals.
(N) Negligible Weathering Region - A climate where concrete is rarely exposed to freezing in the presence of moisture.

Class Designation	Type or Location of Concrete Construction	Maximum Allowable %						
		Clay Lumps and Friable Particles	Chert (Less Than 2.40 sp. gr. SSD)	Sum of Clay Lumps, Friable Particles, and Chert (Less Than 2.40 sp. gr. SSD)	Material Finer Than 75-µm (No. 200) Sieve	Coal and Lignite	Abrasion*	Magnesium Sulfate Soundness (5 cycles)**
1S	Footings, foundations, columns and beams not exposed to the weather, interior floor slabs to be given coverings	10.0	—	—	1.0†	1.0	50	—
2S	Interior floors without coverings	5.0	—	—	1.0†	0.5	50	—
3S	Foundation walls above grade, retaining walls, abutments, piers, girders, and beams exposed to the weather	5.0	5.0	7.0	1.0†	0.5	50	18
4S	Pavements, bridge decks, driveways and curbs, walks, patios, garage floors, exposed floors and porches, or waterfront structures, subject to frequent wetting	3.0	5.0	5.0	1.0†	0.5	50	18
5S	Exposed architectural concrete	2.0	3.0	3.0	1.0†	0.5	50	18
1M	Footings, foundations, columns, and beams not exposed to the weather, interior floor slabs to be given coverings	10.	—	—	1.0†	1.0	50	—
2M	Interior floors without coverings	5.0	—	—	1.0†	0.5	50	—
3M	Foundation walls above grade, retaining walls, abutments, piers, girders, and beams exposed to the weather	5.0	8.0	10.0	1.0†	0.5	50	18

4M	Pavements, bridge decks, driveways and curbs, walks, patios, garage floors, exposed floors and porches, or waterfront structures subject to frequent wetting	5.0	5.0	7.0	1.0[C]	0.5	50	18
5M	Exposed architectural concrete	3.0	3.0	5.0	1.0[C]	0.5	50	18
1N	Slabs subject to traffic abrasion, bridge decks, floors, sidewalks, pavements	5.0	—	—	1.0[C]	0.5	50	—
2N	All other classes of concrete	10.0	—	—	1.0[C]	1.0	50	—

* *Crushed air-cooled blast-furnace slag is excluded from the abrasion requirements. The rodded or jigged bulk density (unit weight) of crushed air-cooled blast-furnance slag shall not be less than 1120 kg/m3 (70 lb/ft3). The grading of slag used in the bulk density (unit weight) test shall conform to the grading to be used in the concrete. Abrasion loss of gravel, or crushed gravel, or crushed stone shall be determined on the test size or sizes most nearly corresponding to the grading or gradings to be used in the concrete. When more than one grading is to be used, the limit on abrasion loss shall apply to each.*

** *The allowable limits for soundness shall be 12% if sodium sulfate is used.*

† *This percentage under either of the follwoing conditions: (1) is permitted to be increased to 1.5 if the material is essentially free of clay or shale; or (2) if the source of the fine aggregate to be used in the concrete is known to contain less than the specified maximum amount passing the 75-μm (No. 200) sieve (Table 1) the percentage limit (L) on the amount in the course aggregate is permitted to be increased to L = 1 + [(P)/(100 - P)] (T-A), where P = percentage of sand in the concrete as a percent of total aggregate, T = the Table 1 limit for the amount permitted in the fine aggregate, and A = the actual amount in the fine aggregate. (This provides a weighted calculation designed to limit the maximum mass of material passing the 75-μm (No. 200) sieve in the concrete to that which would be obtained if both the fine and coarse aggregate were supplied at the maximum tabulated percentage for each of these ingredients.)*

Clay Lumps/Friable Particles

Clay lumps and friable particles can break down into smaller lumps and microfines during concrete production and decrease workability or require more mix water to maintain workability. In hardened concrete, clay lumps at the surface of the concrete can weaken by moisture absorption and disintegrate leaving a void or they can expand causing popouts. ASTM C 142 is the common test method for evaluating the amount of this material.

Coal/Lignite/Other Lightweight Particles

Coal, lignite and other lightweight materials can have similar effects on concrete as clay lumps and friable particles. Near the concrete surface, these materials can disintegrate or pop out which can affect the durability and wearing characteristics of the surface. These materials can also stain the concrete. Like clay lumps and friable particles, particles of these materials can potentially break down during concrete production and thereby increase the water demand to offset the loss of workability. Assessment for these deleterious materials is typically by the ASTM C 123 test method using a heavy liquid with 2.0 specific gravity.

Chert

Lightweight chert particles with a relative density (specific gravity) less than 2.4 readily take on water and become saturated. Freezing of such saturated aggregates particles causes significant volume change that can result in popouts on the surface of concrete. Testing of aggregates in a heavy liquid of 2.40 specific gravity following ASTM C 123 procedures will identify potential chert particles but examination of those particles following ASTM C 295 is necessary to identify if any are chert.

Iron Oxides

Iron oxide expands as it forms. Stress from this expansion causes popouts in the concrete. Even if a popout does not occur, the concrete surface becomes stained. ASTM C 33 does not address this specific issue.

Alkali-Silica Reactivity (ASR)

Some aggregates contain certain siliceous constituents that react with alkali components (potassium and sodium oxides) in concrete. Alkalis are available in cement but there may be additional sources. The product of the alkali-silica reaction is a gel that swells as it adsorbs moisture from within the concrete. The source of moisture can be free mix water from within the cement paste or external water that has permeated into the concrete. If there is a sufficient amount of reactive particles, there can be a significant accumulation of the alkali-silica gel. In turn, if there is adequate moisture available over time, there can be enough swelling of the gel to exert expansive pressure from within the concrete ultimately resulting in cracking and damage to the concrete. Where reactive aggregates particles are near the concrete surface, popouts can occur (Fig. 14.8).

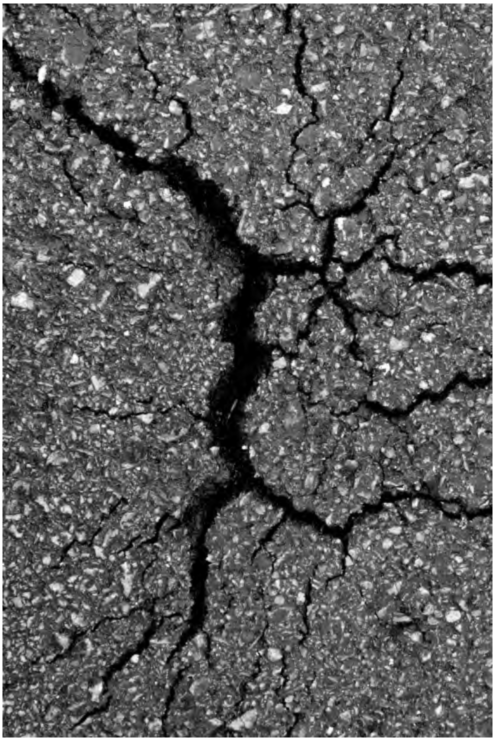


Figure 14.8 Photo of Cracking on Pavement Surface

Some materials identified as being reactive are opal, chalcedony, strained quartz and glass and all highly siliceous material. There are numerous tests available for evaluating aggregates in the laboratory for alkali-silica reaction potential. One or more tests may be required to identify potential reactivity. However, if the source has a good service record, this may suffice as an indicator of performance. Table 14.12 contains a list of the common tests for used by the Federal Highway Administration (FHWA) for potential reactivity.

Historically, little could be done to concrete containing aggregates with ASR. It is best to take preventative measures before concrete production. For some aggregates, adverse alkali-aggregates reactions can be minimized in concrete by limiting the alkali content of the cement to 0.6 percent, expressed as Na_2O equivalent. Limiting the alkalis in the concrete, e.g., 3.5 pounds per cubic yard has been found to be a preferred approach, although even this level of alkalis for highly reactive aggregates has been shown to produce cracking in large scale specimens placed in exposure sites. The most widely used mitigation solution is the addition of an appropriate supplementary cementitious material (SCM). Considerable research has been performed, and it has been concluded that nearly all fly ashes, particularly those with a CaO content of less than 20 percent, are useful in mitigating ASR. Even fly ashes with higher CaO contents are effective, although higher levels, e.g., up to 40 percent, may have to be used. Slag and metakaolin have also been found to be effective in mitigating ASR. Lithium added to fresh concrete has been successfully used, but generally the levels must be determined by long-term tests.

Table 14.12 Test Methods for Potential Alkali-Aggregates Reactivity (Excerpted from Table 5-5, FHWA Publication No. HIF-07-004)

Test Method I.D.	Test Method Title	Test Duration	Comments	Criteria
ASTM C 227	Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar Bar Method)	Usually at least 1 year	Long test. Expansions may not be Alklai-Aggregate Reactivity	ASTM C 33 6 Month Expansion: • 0.10% - excessive
ASTM C 289	Potential Reactivity of Aggregates (Chemical Method)	24 hours	Quick results. Not reliable.	Result plotted on graph. Areas of demarcation: • potentially deleterious • deleterious
ASTM C 295	Petrographic Examination of Aggregates for Concrete	Short duration – visual examination	Optical microscopy, potentially other tests.	
ASTM C 1260 AASHTO T 303	Potential Alkali Reactivity of Aggregates (Mortar Bar Method)	16 days	Fast alternative to C 227. Useful for slowly reacting aggregates	14 Day Expansion: • 0.10% - further testing needed • 0.20% - potentially deleterious
ASTM C 1293	Determination of Length Change of Concrete Due to Alkali-Silica Reaction (Concrete Prism Test)	Usually 1 year or longer when SCMs are used	Long test. Use as a supplement to C 227, C 289, C 295, and C 1260.	1 Year Expansion: • 0.04% - potentially deleterious
Modified ASTM C 1293	Accelerated Concrete Prism Test	91 days	Fast alternative to C 227. Good correlation to C 227 for carbonate and sedimentary rocks	91 Day Expansion: • 0.04% - potentially deleterious
ASTM C 1567	Potential Alkali-Silica Reactivity of Combination of Cementitious Materials and Aggregate (Accelerated Mortar Bar Method)`	16 days	Fast alternative to C 1293. Useful for assessing effects of supplementary cementitious materials	14 Day Expansion: • 0.10% - potentially deleterious, confirm with C 1293

Alkali-Carbonate Reactivity (ACR)

Alkali-carbonate reactions are associated with dolomitic limestone that has the following characteristics:

- Is dolomitic but contains appreciable quantities of calcite;
- Contains clay and/or silt;
- Has an extremely fine-grained matrix; and
- Has a characteristic texture consisting of small, isolated dolomite rhombi disseminated in a matrix of clay, silt-sized quartz and finely divided calcite.

In ACR, the dolomite breaks down when it reacts with alkali hydroxide solution which is referred to as dedolomitization. ACR expansion and the resulting concrete deterioration are analogous to that of ASR. Of the two deleterious conditions, ASR is much more prevalent. Aggregates susceptible to ACR are usually not suitable for concrete due to deficiencies in other properties and therefore the use of such aggregates has been much more limited.

One method for evaluating alkali-carbonate reaction potential is ASTM C 586, the rock cylinder test, which requires a minimum of six months for completion. Petrographic examination per ASTM C 295 and the concrete prism test per ASTM C 1105 are two other common methods. As with ASR, however, previous successful performance of the aggregate in concrete structures is probably the best evidence of having no adverse behavior.

In the mining process, portions of deposits containing ACR-susceptible aggregates should be avoided. If that is not possible, a potential measure for mitigating the overall expansion is to use the smallest nominal maximum size coarse aggregates that are practical. Another potential measure is to blend aggregates such that the coarse or fine aggregates contains no more than 20 percent reactive rock or, if both coarse and fine aggregates contain reactive rock, there is not more than a total of 15 percent reactive rock.

Color and Appearance

For typical concrete, color and color uniformity of the aggregates are not normally a concern. However, for architectural or decorative concrete, these items may be important. The color of concrete made with white or buff colored cement is significantly affected by the color of the fine aggregate. Even the shading of concrete with integral color pigments is affected to some degree. Fine aggregates color also affects the overall color tone of a concrete surface that has been exposed or abraded to a shallow depth by acid etching, abrasive blasting or waterblasting.

For concrete with an exposed aggregates surface, coarse aggregates color, size and shape have a substantial impact on appearance. The color of the coarse aggregates will be predominant in the overall surface appearance particularly for deeper exposure profiles. Often uniformly graded (one sized) or gap-graded coarse aggregates are used in a surface mix or seeded and worked into a concrete surface and then exposed to provide uniform texture and appearance.

For exposed aggregates finishes on vertical surfaces that will be viewed at a distance, larger maximum size coarse aggregates may be needed to convey a textured appearance. On vertical surfaces, cubical or rounded aggregates will generally stay cleaner throughout changing conditions whereas more fractured aggregates are more likely to gather airborne dust and contaminants.

For exposed aggregates concrete flatwork that will subjected to foot traffic, rounded or cubical coarse aggregates are normally desired over highly fractured material. For flatwork that will be ground and polished, fractured aggregates of uniform size is often used.

Chemical Reactivity

Chemical reactivity and chemical attack of concrete can be from constituents within the concrete and from sources external to the concrete. The two different forms of chemical reactivity between aggregate and cement paste (ASR and ACR) are previously in this section. Chlorides can be present in aggregates and, if the soluble chloride content is high enough, can contribute to the corrosion of reinforcing steel in concrete.

Externally, the major conditions for chemical attack of concrete are exposure to sulfates, seawater, salt from seawater, acids and carbonation. The chemical attack is generally on components in the cement paste and not the aggregates. Carbonate aggregates (limestone and dolomite) do normally react with acids, however. A positive consequence from this is the acid can be neutralized in the reaction if it is standing or stagnant as compared to flowing. Siliceous aggregates ordinarily do not react with acids readily but does react with strong solutions of sodium hydroxide.

Strength

Included in Table 2.2 of Chapter 2 are typical strength properties and values for various aggregates types. For the most part, these strength values are well above those of conventional concrete and thus the more critical factors are the strength of the cement paste and the bonding characteristics of the paste to the aggregates particles.

In high-strength concrete, however, the strength of the aggregates does become a critical influence on the strength of the concrete.

Resistance to Degradation and Abrasion

Resistance to degradation and abrasion refers to aggregates ability to resist or withstand the impact and wear that occurs during processing and mixing and the abrasion that occurs later in service. The degradation of aggregates of low abrasion resistance during concrete production generates fines which increases the water requirement of the concrete to maintain workability.

The abrasion resistance of concrete is most significantly impacted by the compressive strength of concrete but it also is affected by the abrasion resistance of aggregates. Abrasion resistance of aggregate is most commonly evaluated by the Los Angeles Abrasion test as described in Chapter 2. Maximum values for Los Angeles Abrasion loss as specified in ASTM C 33 are shown in Table 14.11.

14.4 Portland Cement

Portland cement is a calcium silicate hydraulic cement and is the most widely specified and used cement for construction. There are other hydraulic cements as well as blended cements and discussions on these follow.

Hydration of Portland Cement

Hydration is a complex series of chemical reactions that occurs between portland cement and water. Portland cement contains three primary ingredients:

- Calcium silicates
- Calcium aluminates
- Calcium sulfates

The calcium silicates make up about 65 to 85 percent of the cement and, when they react with water, calcium silicate hydrate and calcium hydroxide are formed. The calcium silicate hydrate compound is the most important reaction product for it is the one primarily responsible for the setting, hardening, and strength development of the cement paste. The calcium hydroxide is the key component when supplementary cementitious materials are used in concrete.

Throughout the stages of chemical reaction between cement and water, heat is generated to varying degrees and is termed heat of hydration. By far, the most significant heat generation is in the very early life of the concrete, particularly the first 24 to 48 hours. In concrete members of larger mass, the temperature of the concrete can become quite elevated due to the slower dissipation of heat from the larger mass.

The rate of the hydration process is temperature dependent. At higher cement paste temperatures, the reaction rate is accelerated and, at lower temperatures, the reaction rate is slowed. Below 14 ºF (-10 ºC), hydration ceases.

For complete hydration to occur, adequate water must be available to the cement for decades. A water-cement ratio of no less than about 0.40 is needed to fully hydrate all of the compounds in cement. To fully hydrate the more important calcium silicate compounds, a water-cement ratio of around 0.25 is needed. In most concrete, complete hydration never takes place due to the typical evaporation of moisture from the concrete that takes place long before the needed time.

Manufacture of Portland Cement

Portland cement is obtained by pulverizing a cement clinker. The raw material used to produce the clinker is a blend of lime-rich materials such as limestone, marble, chalk, marl or oyster shells and silica-based materials such as shale, slate, granite, sand or iron blast furnace slag. As a result of firing a blend of these materials in a rotary kiln, primarily calcium silicates and calcium aluminates are formed. To reduce the rate at which the hydration reaction takes place with water, calcium sulfate (gypsum) is interground with the clinker. The presence of iron in the raw material causes the cement to be a dark color. White portland cement is manufactured by reducing the iron content. A more detailed discussion of the manufacture of portland cement is given in Section 14.6 of Chapter 14. Emphasis on sustainability is focusing on methods to reduce the amount of CO_2 in the production of cement.

Portland Cement Types

The standard specification for portland cement is ASTM C 150. This standard has requirements for both the chemical composition and the physical properties for eight designated types of portland cement. Of the eight types, there are five basic use categories with additional air-entraining versions for three of the categories. Table 14.13 lists the eight types of portland cement with their uses.

Table 14.13 Types of Portland Cement and Their Uses

Portland Cement Type	Description/Use
Type I	For use when the special properties specified for any other type are not required.
Type IA	Air-entraining cement for the same uses as Type I, where air-entrainment is desired.
Type II	For general use, more especially when moderate sulfate resistance or moderate heat of hydration is desired.
Type IIA	Air-entraining cement for the same uses as Type II, where air-entrainment is desired.
Type III	For use when high early strength is desired.
Type IIIA	Air-entraining cement for the same use as Type III, where air-entrainment is desired.
Type IV	For use when a low heat of hydration is desired.
Type V	For use when high sulfate resistance is desired.

Type I portland cement is widely used in all concrete applications (pavements, structures, pipes, etc.) Type II cement may be used for its moderate heat of hydration characteristics in concrete that is placed during hot weather or in large masses. Exposure of concrete to water with a sulfate content between 150 to 1500 parts per million or soil containing 0.10 to 0.20 percent of water-soluble sulfates are considered conditions for moderate sulfate attack warranting the use of Type II cement.

The high early strength characteristics of Type III portland cement are often desired in precast/prestressed concrete, fast-paced construction, cold weather conditions, etc. In applications where massive concrete structures are poured, such as in large concrete dams, Type IV portland cement limits the rate and amount of heat generated during hydration. Type V portland cement should be employed when severe sulfate action is anticipated (sulfate content in water between 150 to 1500 parts per million and water-soluble sulfate content in soil of 0.10 to 0.20 percent).

The three air-entraining cements are produced with an air-entraining material interground with the portland cement clinker. Air-entraining portland cements often are used in concrete in situations where a separately added air-entraining admixture is not available or practical. The drawback to this is the inability to control or adjust the amount of entrained air that is generated in the concrete.

Hydraulic Cements

As defined by ASTM C 219-03, *Standard Terminology Relating to Hydraulic Cement*, hydraulic cement "sets and hardens by chemical reaction with water and is capable of doing so under water." Hydraulic cement is a more encompassing term for cement and it includes portland cement and blended cement. ASTM C 1157 is the standard specification for hydraulic cement and was first approved in 1992. It sets requirements for physical performance of cement as compared to the prescriptive requirements of ASTM C 150 (portland cement) and C 595 (blended hydraulic cement). In a pattern similar to ASTM C 150, C 1157 distinguishes six types of hydraulic cement as illustrated in Table 14.14.

Table 14.14 ASTM C 1157 Types of Hydraulic Cement

Type	Description	Type	Description
GU	Hydraulic cement for general construction. Use when one or more of the special types are not required.	HS	High Sulfate Resistance.
HE	High Early-Strength.	MH	Moderate Heat of Hydration.
MS	Moderate Sulfate Resistance	LH	Low Heat of Hydration.

Blended Hydraulic Cements

ASTM C 219 defines blended hydraulic cement as "hydraulic cement consisting of two or more inorganic constituents (at least one of which is not portland cement or portland cement clinker) which separately or in combination contribute to the strength gaining properties of the cement..." In simple terms, blended hydraulic cement consists of slag or pozzolan blended with portland cement or slag blended with lime. The fundamental constituents for blended hydraulic cement are portland cement, ground granulated blast furnace slag, pozzolans (fly ash, silica fume and natural pozzolans), and hydrated lime. C 595 designates five types of cement for general construction and one for masonry mortar as shown in Table 14.15.

C 595 provides for the option of air-entraining for all six types of blended hydraulic cement and is to be designated with a suffix "A" added to the type. For the five general construction types, provision also is given for the special properties of moderate sulfate resistance and/or moderate heat of hydration. These are to be indicated by the addition of the suffix (MS) or (MH), respectively, to the cement type designation.

Other Types of Cement

There is a multitude of other cements for special or particular applications. A summary of these is provided in Table 14.16.

Table 14.15 ASTM C 595 Blended Hydraulic Cement Types

Type	Name	Blend Criteria
For General Construction		
IS	Portland Blast-Furnace Slag Cement	Portland cement with 25% to 75% blast-furnace slag
IP and P*	Portland-Pozzolan Cement	Portland cement with 15% to 40% pozzolan
I(PM)	Pozzolan-Modified Portland Cement	Portland cement with less than 15% pozzolan
I(SM)	Slag-Modified Portland Cement	Portland cement with less than 25% blast-furnace slag

** Type P is for construction not requiring high early strengths*

For Masonry Mortar		
S	Slag Cement	70% minimum blast-furnace slag with portland cement or lime

Table 14.16 Special Cements and Their Applications (From Table 2.4, PCA DCCM, EB001.14)

Special cements	Type	Application
White portland cements, ASTM C 150	I, II, III, V	White or colored concrete, masonry, mortar, grout, plaster, and stucco
White masonry cements, ASTM C 91	M, S, N	White mortar between masonry units
Masonry cements, ASTM C 91	M, S, N	Mortar between masonry units,* plaster and stucco
Mortar cements, ASTM C 1329	M, S, N	Mortar between masonry units*
Plastic cements, ASTM C 1328	M, S	Plaster and stucco**
Expensive cements, ASTM C 845	E-1(K), E-1(M), E-1(S)	Shrinkage compensating concrete
Oil-well cements, API-10	A, B, C, D, E, F, G, H	Grouting wells
Water-repellent cements		Tile grout, paint, and stucco finish coats
Regulated-set cements		Early strength and repair***
Cements with functional additions, ASTM C 595 (AASHTO M 240), ASTM C 1157		General concrete constructions needing special characteristics such as; water reducing, retarding, air entraining, set control and accelerating properties
Finely ground (ultrafine) cement		Geotechnical grouting***
Calcium aluminate cement		Repair, chemical resistance, high temperature exposures
Magnesium phosphate cement		Repair and chemical resistance
Geopolymer cement		General construction, repair, waste stabilization ***
Ettringite cements		Waste stabilization***
Sulfur cements		Repair and chemical resistance
Rapid hardening hydraulic cement	VH, MR, GC	General paving where very rapid (about 4 hours) strength development is required

** Portland cement Types I, II, and III and blended cement Types IS, IP and I(PM) also are used in making mortar.*

*** Portland cement Types I, II, and III and blended cement Types IP, I(SM) and I(PM) also are used in making plaster.*

**** Portland and blended hydraulic cements also are used for these applications.*

14.5 Supplementary Cementitious Material

Supplementary Cementitious Materials (SCM) supplement the cement by ultimately providing additional cementing compounds in concrete. These materials often have been referred to as mineral admixtures. Depending on the SCM, the additional cementing compounds are developed through hydraulic reactions and/or through pozzolanic reactions. ASTM C 125-06a, *Standard Terminology Relating to Concrete and Concrete Aggregates*, defines a pozzolan as:

> "a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties."

SCMs are used in concrete to substitute for a portion of the cement and/or enhance one or more of the concrete's properties.

Fly Ash

Fly ash is a residue collected from flue gases generated by the burning of finely ground or powdered coal. Fly ash particles are solid or hollow, predominantly spherical in shape, and amorphous. The color of fly ash varies from light tan through shades of gray to black. The tan color usually is associated with increased amounts of lime; darker colors are indicative of increased amounts of carbon. The relative density (specific gravity) is typically between 1.9 and 2.8.

Specification requirements for fly ash are given in ASTM C 618, *Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete*. There are two classes of fly ash included in the standard: F and C. Class F fly ash is obtained from the burning of anthracite or bituminous coal. The additional cementitious material produced from Class F fly ash is by pozzolanic activity. Class C fly ash is obtained from the burning of subbituminous coal and lignite. Additional cementitious materials from Class C fly ash usually are generated by both pozzolanic and hydraulic activity. In fresh concrete, fly ash generally improves workability and pumpability and reduces segregation, bleeding and heat generation. Fly ash in hardened concrete generally reduces permeability and increases later age strength. Class F fly ash also is primarily associated with enhanced sulfate resistance and reduced expansion from alkali-silica reaction. For resistance to deicer-scaling, ACI 318, the building code for structural concrete, limits the maximum amount of fly ash to 25 percent of the total cementitious material. See Table14.17 for the various effects of fly ash on concrete.

Table 14.17 Effects of SCM's on Fresh Concrete Properties

	Fly ash				Natural pozzolans		
	Class F	Class C	GGBF Slag	Silica fume	Calcined shale	Calcined clay	Metakaolin
Water requirements	↓↓	↓↓	↓	↑↑	↔	↔	↑
Workability	↑	↑	↑	↓↓	↑	↑	↓
Bleeding and segregation	↓	↓	↕	↓↓	↔	↔	↓
Air content	↓↓	↓	↓	↓↓	↔	↔	↓
Heat of hydration	↓	↕	↓	↔	↓	↓	↓
Setting time	↑	↕	↑	↔	↑	↑	↔
Finishability	↑	↑	↑	↕	↑	↑	↑
Pumpability	↑	↑	↑	↑	↑	↑	↑
Plastic shrinkage cracking	↔	↔	↔	↑	↔	↔	↔
Early strength	↓	↔	↓	↑↑	↓	↓	↑↑
Long-term strength	↑	↑	↑	↑↑	↑	↑	↑↑
Permeability	↓	↓	↓	↓↓	↓	↓	↓↓
Chloride ingress	↓	↓	↓	↓↓	↓	↓	↓↓
ASR	↓↓	↕	↓↓	↓	↓	↓	↓
Sulfate resistance	↑↑	↕	↑↑	↑	↑	↑	↑
Freezing and thawing	↔	↔	↔	↔	↔	↔	↔
Abrasion resistance	↔	↔	↔	↔	↔	↔	↔
Drying shrinkage	↔	↔	↔	↔	↔	↔	↔

Sources: Thomas and Wilson (2002b); Kosmatka, and Panarese (2003)

** Effect depends on properties of fly ash, including carbon content, alkali content, fineness, and other chemical properties.*

Key:
- ↓ Reduced
- ↓↓ significantly reduced
- ↑ Increased
- ↑↑ significantly increased
- ↔ no significant change
- ↕ effect varies

Natural Pozzolans

A natural pozzolan is "a raw or calcined natural material that has pozzolanic properties (for example, volcanic tuffs or pumicites, opaline cherts and shales, clays and diatomaceous earths)" as defined by ACI 116R-00, *Cement and Concrete Terminology*. Natural pozzolans are included in ASTM C 618 with a Class N classification. The most commonly used natural pozzolans are calcined products (heated in a kiln below the fusion temperature and ground to a fine powder). Among these materials are calcined clay, calcined shale and metakaolin.

Broadly speaking, natural pozzolans generally improve workability and reduces segregation, bleeding and heat generation in fresh concrete. In hardened concrete, they generally reduce permeability, reduce expansion from alkali-silica reaction, increase later age strength and enhance sulfate resistance. As with fly ash, the amount of pozzolans in concrete is limited in ACI 318 to a maximum to 25 percent of the total cementitious material. See Table 14.17 for a more complete view of the effects of natural pozzolans on concrete.

Calcined clay, like fly ash, can be used as a substitute for a portion of the cement typically in the range of 15 to 35 percent. The relative density (specific gravity) of calcined clays is usually between 2.4 and 2.6. Calcined clays can reduce permeability, increase resistance to sulfate attack and reduce alkali-silica reactivity expansion. Calcined shale with calcium contents of 5 to 10 percent can have hydraulic properties as well as pozzolanic properties. A typical relative density for calcined shale is 2.6. Metakaolin is made from high purity kaolin clay calcined at temperatures of 1112 to 1472 ºF (600 to 800 ºC). Relative density is normally in the range of 2.5 to 2.6. Metakaolin is typically used in addition to cement and can significantly reduce permeability and increase strength.

Silica Fume

Silica fume is a pozzolan and specified in ASTM C 1240. It also is known as microsilica or condensed silica fume and, like fly ash, is a byproduct. The silicon or ferrosilicone industries use electric arc furnaces to reduce high purity quartz with coal. In the process, a molten metal is produced emitting a silica-based vapor. As this vapor rises, it rapidly cools and condenses forming extremely small, glassy, spherical particles of silicon oxide. The condensed silica fume is collected in cloth bags and then processed to remove impurities and agglomerate the extremely fine particles into a more densified condition.

The relative density of silica fume is in the range 2.2 to 2.6. The proportion of silica fume in concrete is usually between 5 and 10 percent by mass of the total cementitious material. Silica fume is generally used to produce a concrete with very low permeability and/or high strength. For deicer-scaling resistance, ACI 318 limits the amount of silica fume to a maximum of 10 percent of the total cementitious material.

Due to the fineness of silica fume, the amount of mix water required for the workability of the concrete may be high. It is very common to use high range water reducers with silica fume. The fineness of the silica fume also markedly decreases bleeding in concrete thus highly increasing the potential for plastic shrinkage cracking. Table 14.17 shows the effects of silica fume on various concrete properties.

Slag

Slag cement and ground granulated blast-furnace slag are synonymous terms referring to the hydraulic cement made by finely grinding granulated blast-furnace slag. In the smelting of iron ore, blast-furnace slag is the nonmetallic molten byproduct that is simultaneously developed with the molten iron in a blast furnace. The molten slag becomes granulated blast-furnace slag when it is drained from the furnace and rapidly quenched in cold water forming glassy, sand-like granules.

Slag cement primarily consists of silicates and aluminosilicates of calcium which are the same elementary constituents of portland cement. Because of its chemistry, slag cement reacts hydraulically, without the presence of added calcium, although the rate at which it hydrates is accelerated when the pH of the cement paste is increased. The relative density (specific gravity) of slag cement is generally between 2.85 to 2.95, closer to that of portland cement than any of the other supplementary cementitious materials.

ASTM C 989 is the common specification for slag cement. It has three strength grades: 120, 100 and 80 that are based on the relative mortar strength of a slag-portland cement mortar relative to that of a reference portland cement mortar. Slag cement is commonly used in concrete at a proportion of 30 to 45 percent of the total cementitious material yet some concretes have had a slag content of 70 percent or more of the cementitious material.

In fresh concrete, slag generally improves workability and, at greater than 25 percent replacement of portland cement, setting time is slightly increased. In hardened concrete, it reduces expansion from alkali-silica reaction, decreases strength at the very early ages but increases later age strength, and improves sulfate resistance, and greatly reduces permeability. ACI 318 limits the maximum amount of slag to 50 percent of the total cementitious material if resistance to deicer-scaling is required. See Table 14.17 for a more complete view of the effects on concrete.

14.6 Mix Water

In 2004, a new ASTM standard was approved for concrete mix water, C 1602, *Standard Specification for Mixing Water Used in Production of Hydraulic Cement Concrete*. This specification defines the potential sources of Mixing Water, establishes the requirements for the physical performance of concrete made with the water, provides optional requirements for chemical composition of the water and, and provides protocol and frequencies for the testing of water.

Sources

ASTM C 1602 states that mixing water is from any or all of the following sources:
- Batch water (water weighed or metered through the batch plant)
- Ice
- Water added by truck operator
- Free moisture on the aggregates
- Water introduced in the form of admixtures when this water increases the water-cementitious materials ratio by more than 0.01

Batch water typically comes from any of the common sources of natural fresh water such as domestic water systems or private supplies (e.g., wells, ponds) but also can include recovered water from concrete production operations. When water is utilized from two or more of sources, it is referred to as combined water.

The portion of water contained in admixtures is usually not a concern because the admixture dosage amount is often very small in relation to the total amount of mixing water. However, higher dosages of non-chloride accelerators and high range water reducers can contribute additional water to such an extent that the water-cementitious ratio is impacted beyond the 0.01 amount.

Water Quality

Mixing water that is potable is acceptable for use as is and there is no need for any compliance testing. Mixing water must be tested for compliance to ASTM C 1602 criteria if it contains non-potable water or water from concrete production operations. The concrete performance requirements for mixing water are shown in Table 14.18. Table 14.19 contains the optional compositional requirements for combined mixing water. Any or all of these optional requirements are to be specified by the purchaser of the concrete if conditions for the concrete application warrant them. For example, if concrete will be exposed to high sulfate soils, the limits on sulfates in the combined mixing water should be specified.

Mixing water compliance testing for concrete performance and chemical composition (if specified) must be conducted before the first use. The required frequency of compliance testing thereafter is provided in detail in ASTM C 1602. For ascertaining the needed performance testing frequency for mixing water containing water from concrete production operations, daily determinations of the density of the mixing water is required.

Table 14.18 Concrete Performance Requirements for Mixing Water (From ASTM C 1602/C 1602M – 06 Table 1)

	Limits	Test Methods
Compressive strength, min % control at7 days*,**	90	C 31/C 31M, C 39/C 39M
Time of set, deviation from control, h:min*	From 1:00 early to 1:30 later	403/C 403M

* *Comparisons shall be based on fixed proportions for a concrete mix design representative of questionable water supply and a control mix using 100% potable water or distilled water. (See Annex A1).*

** *Compressive strength results shall be based on at least two standard test specimens made from a composite sample.*

Table 14.19 Optional Chemical Limits for Combined Mixing Water (From ASTM C 1602/C 1602M – 06 Table 2)

	Limits	Test Method
Maximum concentration in combined mixing water, ppm**		
A. Chloride as Cl , ppm		
1. in prestressed concrete, bridge decks, or otherwise designated	500†	C 114
2. other reinforced concrete in moist environments or containing aluminum embedments or dissimilar metals or with stay-in-place galvanized metal forms	1000†	C 114
B. Sulfate as SO_4: ppm	3000	C 114
C. Alkalies as (Na_2O + 0.658 K_2O), ppm	600	C 114
D. Total solids by mass, ppm	50 000	C 1603

* *Specification limits from this table are not prohibited from being specified as individual or as a whole per paragraph 4.1.6 of Specification C 94/C 94M.*

** *ppm is the abbreviation for parts per million.*

† *The requirements for concrete are ACI 318 shall govern when the manufacturer can demonstrate that these limits for mixing water can be exceeded. For conditions allowing the use of calcium chloride ($CaCl_2$) accelerator as an admixture, the chloride limitation is permitted to be waived by the purchaser.*

14.7 Admixtures

The fundamental ingredients of concrete are cement, water and aggregates. All other ingredients that are added to a concrete batch before or during mixing are considered admixtures. Supplementary cementitious materials (mineral admixtures) are covered in other portions of this chapter. Admixtures are primarily used to reduce the cost of the concrete mixture and/or the concrete construction, increase the efficiency of cementitious material, and modify or enhance the fresh and/or hardened properties of concrete. The effectiveness of admixtures is contingent upon a multitude of factors including the properties of the cementitious materials, water content, properties of the aggregate, compatibility with other admixtures, proportions of the concrete constituents, mixing time and intensity and concrete temperature.

Air-Entraining Admixtures

Air-entraining admixtures are used to produce well-spaced microscopic air bubbles in the cement paste of concrete. In fresh concrete, entrained air increases workability, reduces water demand, decreases the tendency for mixture segregation and decreases bleeding. In hardened concrete, it significantly enhances resistance to freeze-thaw damage and to deicer scaling. Typically air contents of 5 to 7 percent are used in air entrained mixes with ¾- to 1-inch (19 to 25 mm) nominal maximum size aggregates. Entrained air can be generated in concrete by the use of air-entraining cement, by the use of a separate air-entraining admixture introduced into the concrete batch before or during mixing, or by the use of both.

Air-entraining admixtures are typically derived from pine wood resins, vinsol resins, and other synthetic detergents. The most common standards pertaining to air-entraining admixtures are ASTM C 260 and C 233 (AASHTO M 154 and T 157). ASTM C 226 pertains to air-entraining materials added in the manufacture of air-entraining cements.

Water-Reducing Admixtures

Water-reducing admixtures can be used to increase concrete workability or maintain workability while decreasing water content about 5 to 10 percent. The reduced water content usually results in less drying shrinkage. It also lowers the water-cement ratio which results in higher strength. Many water-reducing admixtures will often retard the setting time of concrete particularly if overdosed. These admixtures usually are added to the concrete at the concrete batch plant. The dosage of the admixture is varied to achieve the desired slump or water reduction.

Water-reducing admixtures generally consist of lignosulfonates, hydroxylated carboxylic acids or carbohydrates. Water-reducing admixtures are specified as Type A chemical admixtures by ASTM C 494 (AASHTO M 194). ASTM C 494 (AASHTO M 194) also addresses chemical admixtures that are both water-reducing and set-controlling admixtures. These reduce the water requirements of a concrete mixture for a given slump and modify the time of setting. Some of these water-reducing/set-controlling admixtures can entrain excessive amounts of air. Water-reducing and accelerating admixtures are Type E chemical admixtures and water-reducing and retarding admixtures are Type D chemical admixtures. See the following sections on Accelerating Admixtures and Retarding Admixtures for further discussion on set-controlling admixtures.

Mid-Range Water Reducing Admixtures

Mid-range water reducers can be used to increase workability and slump or maintain slump and decrease water content by 6 to12 percent. These admixtures tend to be more stable over a wider range of temperatures and do not have the retardation associated with high dosages of normal water reducers. For certain concrete mixtures containing supplementary cementing materials that can have a tendency to be "sticky", particularly those with silica fume, mid-range water reducing admixtures can help alleviate the "stickiness" and enhance the pumping and finishing characteristics of those mixtures. Mid-range water reducers are appropriate for concrete flatwork as well as low slump slip form applications.

Mid-range water reducers generally consist of a combination of natural, petroleum-based, and/or polycarboxylate chemical compounds, the same compounds which can be found in some high range water reducers or newer normal water reducers. There is not a separate ASTM C 494 (AASHTO M 194) designation for these admixtures. They generally meet the criteria for both Type A and Type F chemical admixtures.

High-Range Water Reducing Admixtures

High-range water reducing admixtures also are known as plasticizers and superplasticizers. This group of admixtures is capable of reducing the water in a concrete mix by 12 to 30 percent. High-range water reducers can be used to produce cohesive, high-slump (in excess of 8 inches (200 mm)), flowing concrete that can be placed with little or no consolidation efforts. In contrast, they also can be used to produce concrete of a normal slump yet very low water-cement ratio and hence high strength, or to reduce the cement content in a mix for purposes of economy. Various high-range water reducing products are available. Some have a longer lasting effect on slump and are commonly added at the concrete plant. Others are effective for shorter periods of time (30 to 60 minutes) and thus are typically added in the truck mixer at the job site.

Chemical compounds typical to high-range water reducing admixtures are sulfonated naphthalene condensates, sulfonated melamine condensates, modified lignosulfonates and polycarboxylates. High-range water reducing admixtures are specified as Type F chemical admixtures by ASTM C 494 (AASHTO M 194). Type G chemical admixtures are high-range water reducing and retarding admixtures.

Most high-range water reducers also meet the requirements of ASTM C 1017, the specification for chemical admixtures used to produce flowing concrete. ASTM C 1017 defines flowing concrete as having a slump greater than 7.5 inches (190 mm) while remaining cohesive. Two types of chemical admixtures are addressed in C 1017: Type I, Plasticizing and Type II, Plasticizing and Retarding.

Retarding Admixtures

Retarding admixtures increase the time of set of the concrete where longer working time is required or where high temperatures would otherwise cause early setting. They often are used in the summer months to give finishers sufficient time to adequately finish concrete surfaces. The dosage of retarding admixture is varied in concrete mixes to obtain the desired extension of set time. There are some other characteristics of retarded concrete mixtures, however, that should be understood. At elevated temperatures, there can be a faster and greater slump loss. With retarded concrete, there typically is an increase in the amount of bleed water and the rate at which it bleeds. Also, early strengths are typically lower in concrete containing a retarder.

Lignin, borax, sugars, and tartaric acid and salts are typical components of retarding admixtures. Retarders are designated as a Type B chemical admixture in ASTM C 494 (AASHTO M 194). As stated in the discussion on water reducers, Type D chemical admixtures have both water-reducing and retarding effects.

Accelerating Admixtures

Accelerating admixtures increase the rate of hydration thus decreasing the time of set and increasing the early age strength development of concrete. Accelerators normally are used in cold weather to reduce the time required to finish concrete or to provide high early concrete strengths at normal temperatures.

Calcium chloride has been the most commonly used accelerating admixture. It is economical and very effective in accelerating set and strength gain but it promotes the corrosion of steel within the concrete. In addition, concrete with calcium chloride can experience rapid stiffening, increased drying shrinkage, discoloration and lower potential strength at later ages. Requirements specific to calcium chloride are contained in ASTM D 98 (AASHTO M 144).

Admixture manufacturers have now produced noncorrosive accelerators that do not contain chlorides. These nonchloride accelerating admixtures are made of triethanolamine, sodium thiocyanate, calcium formate, calcium nitrite or calcium nitrate. Accelerators are designated as Type C admixtures under ASTM C 494 (AASHTO M 194). Type E admixtures have both water-reducing and accelerating effects.

Other Admixtures

There is a wide range of other admixtures with various specific functions. Table 14.20 provides a list of some of these other admixtures.

Table 14.20 Other Common Admixtures

Type of Admixture	Standard Specification	Desired Effect
ASR-inhibiting admixture		Reduce or eliminate expansion from alkali-silica reaction
Coloring admixtures (pigments)	ASTM C 979	Colored concrete
Corrosion Inhibitors	ASTM C 1582	Minimize steel reinforcement corrosion
Damp proofing admixture		Retard moisture penetration into dry concrete
Hydration control admixtures		Suspend and reactivate concrete hydration
Shinkage-reducing admixtures		Reduce drying shrinkage in concrete
Viscosity-modifying admixtures		Modify the viscosity/control the deformation and flow characteristics of fresh concrete

14.8 Portland Cement Concrete Mixture Design

There are many factors that influence or define the requirements of a concrete mixture for an intended application including construction conditions, physical constraints, structural loading conditions and short- and long-term exposure conditions. The ultimate development of a concrete mixture involves both the design and the proportioning of the mixture.

Mix Design

Mix design is the process of determining the needed properties of both fresh and hardened concrete as well as the requirements and limitations for specific mix constituents.

Mix Properties

- Strength
- Slump
- Maximum aggregate size
- Air content
- Water-cementitious materials ratio

Strength: The required strength of concrete is generally dependent upon the structural needs of the application and, hence, normally specified by the project designer. For most applications, compressive strength is the applicable design strength but, for some applications such as pavements, it is flexural strength. Some specifications such as ACI 318-05 also place requirements on compressive strength for durability reasons. See Tables 14.24 and 14.25.

Concrete strength is determined from molded specimens that are cured under prescribed conditions and then tested for ultimate strength in a loading device in a laboratory. ASTM C 31 is the standard for molding and curing both compressive strength cylinders and flexural strength beams in the field. ASTM C 192 is the standard for specimens molded in the laboratory. Concrete cylinders are tested for compressive strength following the requirements of ASTM C 39 whereas ASTM C 78 specifies the testing of concrete beams.

For concrete mixtures, it is necessary to have a tolerance criteria or an over-design above the specified strength in order to have a high probability that the concrete will consistently yield a strength equal to or greater than specified. ACI 214 contains a detailed discussion on this issue and ACI 301 and ACI 318 contain required over-design criteria for compressive strength for structural concrete. As an example, a specified compressive strength (f'_c) of 4000 psi (28 MPa) would require an over-design of 1200 psi (8 MPa) for a concrete production facility that does not have adequate field strength test records for statistical evaluation for a possibly lower over-design. Thus, the required average strength (f'_{cr}) of the concrete mixture would be 5200 psi (36 MPa).

Slump: Slump is the measure of the consistency or flowability of fresh or plastic concrete and is indirectly a measure of workability. In the slump test, ASTM C 143 (AASHTO T 119), a sample of concrete is placed in a slump mold, consolidated and struck off following specified procedures. The mold is then lifted allowing the concrete to "slump" or settle. The amount of drop of the top surface is measured and expressed in inches as the slump of the concrete. For conventional concrete, upper limitations are generally placed on slump values because there is a strong tendency for segregation in concrete with excessive slump. Methods of concrete placement and consolidation also can dictate restrictions on slump. Table 14.22 shows commonly accepted slump values for different applications. These limitations can be increased when mid- or high-range water reducers are utilized to achieve higher slump since these admixtures help maintain cohesiveness in the mixture.

The consistency of concrete is equated with the plastic concrete's ability to flow and is most commonly measured by slump.

Table 14.21 Recommended Slumps for Various Types of Construction
(from Table 6.3.1, ACI 211-91)

Types of construction	Slump, in. (mm)	
	Maximum+	Minimum
Reinforced foundation walls and footings	3 (75)	1 (25)
Plain footings, caissons, and substructure walls	3 (75)	1 (25)
Beams and reinforced walls	4 (100)	1 (25)
Building columns	4 (100)	1 (25)
Pavements and slabs	3 (75)	1 (25)
Mass concrete	2 (50)	1 (25)

* *Slump may be increased when chemical admixtures are used, provided that the admixture-treated concrete has the same or lower water-cement or water cementitious material ratio and does not exhibit segregation potential or excessive bleeding.*

\+ *May be increased 1 in. (25 mm) for methods of consolidation other than vibration.*

Maximum Aggregates Size: As a practical matter, the maximum size of aggregates must be limited to assure that the fresh concrete can be placed and consolidated into all of the required spaces without the occurrence of segregation and/or voids. The generally accepted limits for aggregates size are:

- One-fifth the narrowest dimension of a concrete member;
- Three-fourths the clear spacing between reinforcing bars, bundles of bars or pretensioning strands; and
- One-third the depth of slabs.

Air Content: Conventional concrete that will be subjected to freeze-thaw conditions and applications of deicers must have entrained air. Entrained air also can be used for improving workability. The severity of the freeze-thaw conditions and the nominal maximum size of aggregates determine the volume of entrained air that is needed in the concrete for adequate freeze-thaw resistance. The two most common methods for measuring air content in fresh concrete are ASTM C 231 and C 173. Since these methods measure total air content (entrapped plus entrained), recommendations and specifications for air content are based on the total volume of air. Table 14.22 contains typical required air contents for different exposure conditions and aggregates sizes.

Table 14.22 Target Air Content* of Concrete (from Table 4.2.2.4, ACI 301-99)

Nominal maximum size of aggregates, in. (mm)	Air content, + percent		
	Severe exposure	Moderate exposure	Mild exposure
Less than ⅜ (9.5)	9	7	5
⅜ (9.5)	7.5	6	4.5
½ (12.5)	7	5.5	4
¾ (19)	6	5	3.5
1 (25)	6	4.5	3
1-½ (37.5)	5.5	4.5	2.5
2 (50)	5	4	2
3 (75)	4.5	3.5	1.5
6 (150)	4	3	1

* *Measured in accordance with ASTM C 231, C 173, or C138.*

\+ *Air-content tolerance is >/< 1.5%*

Water-Cementitious Materials Ratio: Water-cementitious material ratio, w/cm, significantly impacts the strength, permeability, and durability of a concrete mixture. For strength, the necessary w/cm is determined in the mixture proportioning. For permeability and durability needs, limits for w/cm are usually established in the mixture design. Table 14.23 shows limitations on w/cm for various permeability and durability needs. Table 14.24 shows required w/cm for sulfate resistance.

Table 14.23 Requirements for Special Exposure Conditions (from Table 4.2.2, ACI 318-05)

Exposure condition	Maximum water-cementitious material ratio*, by weight, normal-weight concrete	Minimum f'_c normal-weight and light-weight concrete, psi (MPa)*
Concrete intended to have low permeability when exposed to water.	0.50	4000 (28 MPa)
Concrete exposed to freezing and thawing in a moist condition or to deicing chemicals.	0.45	4500 (31 MPa)
For corrosion protection of reinforcement in concrete exposed to chlorides from deicing chemicals, salt, salt water, brackish water, seawater or spray from these sources.	0.40	5000 (35 MPa)

Table 14.24 – Requirements for Concrete Exposed to Sulfate-Containing Solutions
(from Table 4.3.1 – ACI 318-05)

Sulfate exposure	Water soluble sulfate (SO_4) in soil, percent by weight	Sulfate (SO_4) in water, ppm	Cement type	Maximum water-cementitious material ratio, by weight, normal-weight concrete*	Minimum f'c, normal-weight and light-weight concrete, psi (MPa)*
Negligible	$0.00 \leq SO_4 < 0.10$	$0 \leq SO_4 < 150$	–	–	–
Moderate†	$0.10 \leq SO_4 < 0.20$	$150 \leq SO_4 < 1{,}500$	II, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)	0.50	4000 (28 MPa)
Severe	$0.20 \leq SO_4 \leq 2.00$	$1500 \leq SO_4 \leq 10{,}000$	V	0.45	4500 (31 MPa)
Very severe	$SO_4 > 2.00$	$SO_4 > 10{,}000$	V plus pozzolan‡	0.45	4500 (35 MPa)

**When both Table 4.3.1 and Table 4.2.2 are considered, the lowest applicable maximum water cementitious material ratio and highest applicable minimum f'_c shall be used.*

† Seawater

‡ Pozzolan that has been determined by test or service record to improve sulfate resistance when used in concrete containing Type V cement.

Materials Requirements

- Cementitious materials
- Aggregate
- Admixtures

For certain applications, it may be necessary to restrict or stipulate types of constituent materials and/or set upper or lower limits on proportions of the constituent materials.

Cementitious Materials: Table 14.24 contains requirements on types of cement for concrete exposed to sulfate conditions. Massive concrete structures may warrant the specification of a low heat of hydration cement. The potential use of alkali-silica reactive aggregates may warrant the specification of low alkali cement. It may also warrant the specification of a supplementary cementitious material and the restriction of certain fly ashes. Silica fume may be excluded from use in concrete flatwork. ACI 301 specifies minimum contents of cementitious material for concrete floors (see Table 14.25, unless it can be verified that "concrete mixtures with a lower cementitious-materials content will meet the specified strength requirements and will produce concrete with equal finish quality, appearance, durability and surface hardness." For concrete exposed to deicers, ACI 318 places limits on supplementary cementitious materials proportions as shown in Table 14.26.

Table 14.25 Minimum Cementitious-materials Content Requirements for Floors (from Table 4.2.2.1, ACI 301-99)

Nominal maximum size of aggregate, in. (mm)	Minimum cementitious-materials content, lb/yd³ (kg/m³)
1-½ (37.5)	470 (7529)
1 (25)	520 (8330)
¾ (19)	540 (8650)
⅜ (9.5)	610 (9771)

Note: When fly ash is used, quantity shall not be less than 15% nor more than 25% by weight of total cementitious materials.

Table 14.26 Limitations on Supplementary Cementitious Materials for Concrete Exposed to Deicing Chemicals (from Table 4.2.3, ACI 318-05)

Cementitious materials	Maximum percent of total cementitious materials by weight*
Fly ash or other pozzolans conforming to ASTM C 618	25
Slag conforming to ASTM C 989	50
Silica fume conforming to ASTM C 1240	10
Total of fly ash or other pozzolans, slag and silica fume	50†
Total of fly ash or other pozzolans and silica fume	35†

* *The total cementitious material also includes ASTM C 150, C 595, C 845, and C 1157 cement.*
The maximum percentages above shall include:
(a) Fly ash or other pozzolans present in Type IP or I(PM) blended cement, ASTM C 595, or ASTM C 1157;
(b) Slag used in the manufacture of a IS or I(SM) blended cement, ASTM C 595, or ASTM C 1157;
(c) Silica fume, ASTM C 1240, present in a blended cement.
† *Fly ash or other pozzolans and silica fume shall constitute no more than 25 and 10%, respectively, of the total weight of the cementitious materials.*

Aggregates: Any aggregates susceptible to alkali-silica reactivity (ASR) may need to be prohibited if circumstances do not allow for the use of any ASR-mitigating materials. If alkali-carbonate reactive aggregates must be used, limits should be set on the maximum size or the maximum proportion contained in the total aggregates. Architectural or special use concrete may require more specific or narrowed aggregates gradation limits, specific particle shape characteristics, limited absorption characteristics or restrictions on minimum or maximum aggregates relative density.

Admixtures: Admixtures containing chlorides should be prohibited for reinforced or prestressed concrete, concrete containing aluminum, dissimilar metals, ASR-susceptible aggregates or concrete exposed to sulfates. Lithium admixtures may be specified for mitigation of alkali-silica reactivity expansion, particularly if appropriate supplementary cementitious materials are not allowed or available. High-range water reducers or superplasticizers should be specified when slumps greater than 5 inches are allowed or required. Particular circumstances may necessitate the specification of specialized admixtures such as shrinkage reducing admixtures, corrosion inhibiting admixtures or dampproofing admixtures.

Mix Proportioning

Mix proportioning refers to the systematic approach of selecting appropriate component materials and determining appropriate relative amounts of those materials to produce a concrete mixture that satisfies the mix design requirements. If there is an existing concrete mixture that fulfills all of the design requirements and has acceptable strength test data such as that required in ACI 318, that mixture can be utilized for the application and no further proportioning work is needed. Otherwise, a concrete mixture can be proportioned from field experience, from laboratory trials or by calculation.

When concrete mixtures are proportioned by interpolating between two or more test records from existing concrete mixes, the materials and conditions of those existing mixes should be the same or similar to those needed for the new mix design requirements. For validation of average strength potential, ACI 318 requires that the data for each existing mix be from at least 10 sets of strength tests representing concrete produced over a period of at least 45 days.

For mixtures proportioned from laboratory trials' data, the lab mixes should be batched with the same materials and at the most severe limits expected in the field for water-cementitious material ratio (w/cm), air content and slump. Laboratory trials are normally conducted following the standards of ASTM C 192. ACI 318 requires at least three trial mixes with varying w/cm ratios that will produce a range of strengths encompassing the average required strength. The trials are to have a slump within 0.75 inches (19 mm) of the maximum specified and air content within 0.5 percent of the allowable maximum. From the trials' data, the relationship between strength and w/cm ratio can be plotted as a curve and the appropriate w/cm ratio interpolated so that final proportions can be determined.

If data are not available from existing field mixes or existing laboratory trials, mixtures can be proportioned by calculation using the guidelines contained in ACI 211.1 as presented in the following portions of this section. There is a risk in producing field concrete directly from the calculated proportions since they are based on general values and relationships. Using the calculated proportions, it is best to prepare and test laboratory trial batches so that water demand and materials' compatibility can be verified and an accurate relationship of strength to w/cm ratio can be established.

The proportioning values and calculations that follow are all based on one cubic yard or 27 cubic feet.

Materials Selection

Specifications for the necessary properties of the individual materials were determined in the mixture design. Here, the specific materials must be selected from available sources and with a view toward comparative costs. Selections must be made on the particular cement, supplementary cementitious material (SCM), coarse and fine aggregates and admixtures.

Decisions must be made on the relative amount(s) of SCMs as a percent of the total cementitious material. Decisions also must be made regarding the admixtures as to the respective ranges of dosage for a unit amount (usually 100 pounds) of either cement or cementitious material.

Required Mixing Water Content

The required amount of mixing water to produce a particular slump in a concrete mixture is affected by many factors including air content, the use and dosage of various water reducing admixtures, the characteristics of individual component materials and the inter-relationship between the materials. Experience with local materials and mixes or from previous lab trials is often the best criteria for judging needed water content. In the absence of this, water content can be estimated from Table 14.27. To properly use this table, the target slump, air content and general particle shape of the coarse aggregates must be known. Also, if a water reducing admixture is used, the anticipated amount of water reduction must be known or estimated. Parameters for the information in this table are shown in the footnotes of the table.

Table 14.27 Approximate Mixing Water Requirements (from Table 6.3.3, ACI 211.1-91)

Water, lb/yd^3 of concrete for indicated nominal maximum sizes of aggregates								
Slump, in.	**⅜ in. ***	**½ in. ***	**¾ in. ***	**1 in. ***	**1-½ in. ***	**2 in. *†**	**3 in. †‡**	**6 in. †‡**
Non-air-entrained concrete								
1 to 2	350	335	315	300	275	260	220	190
3 to 4	385	365	340	325	300	25	245	210
6 to 7	410	385	360	340	315	300	270	---
More than 7*	---	---	---	---	---	---	---	---
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1	0.5	0.3	0.2
Air-entrained concrete								
1 to 2	305	295	280	270	250	240	205	180
3 to 4	340	325	305	295	275	265	255	200
6 to 7	365	345	325	310	290	280	260	---
More than 7	---	---	---	---	---	---	---	---
Recommended averages§ total air content, percent for level of exposure:								
Mild exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5**††	1.0**††
Moderate exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5**††	3.0**††
Severe exposure‡‡	7.5	7.0	6.0	6.0	5.5	5.0	4.5**††	4.0**††

* *The quantities of mixing water given for air-entrained concrete are based on typical total air content requirements as shown for "moderate exposure" in the table above. These quantities of mixing water are for use in computing cement contents for trial batches at 68 to 77 F. They are maximum for reasonably well-shaped angular aggregates graded within limits of accepted specifications. Rounded aggregate will generally require 30lbs less water for non-air-entrained and 25 lbs less for air-entrained concretes. The use of water reducing chemical admixtures, ASTM C 494, may also reduce mixing water by 5% or more.*

The volume of the liquid admixtures is included as part of the total volume of the mixing water. The slump values of more than 7 in. are only obtained through the use of water-reducing chemical admixture; they are for concrete containing nominal maximum size aggregates not larger than 1 in.

† The slump values for concrete containing aggregates larger than 1.5 in. are based on slump tests made after removal of particles larger than 1.5 in. by wet-screening.

‡ These quantities of mixing water are for use in computing cement factors for trail batches when 3 or 6 in. nominal maximum size aggregate is used. They are average for reasonably well-shaped coarse aggregates, well-graded from coarse to fine.

§ Additional recommendations for air-content and necessary tolerances on air content for control in the field are given in a number of ACI documents, including ACI 201, 345, 318, 301 and 302. ASTM C 94 for ready-mixed concrete also gives air-content limits. The requirements in other documents may not always agree exactly, so in proportioning concrete consideration must be given to selecting an air content that will meet the needs of the job and also meet the applicable specifications.

** For concrete containing large aggregates that will be wet-screened over the 1.5 in. sieve prior to testing for air content, the percentage of air expected in the 1.5 in. minus material should be as tabulated in the 1.5 in. column. However, initial proportioning calculations should include the air content as a percent of the whole.

†† When using large aggregates in low cement factor concrete, air entrainment need not be detrimental to strength. In most cases mixing water requirement is reduced sufficiently to improve the water-cement ratio and to thus compensate for strength-reducing effect of air-entrained concrete. Generally, therefore, for these large nominal maximum sizes of aggregate, air contents recommended for extreme exposure should be considered even though there may be little or no exposure to moisture and freezing.

‡‡ These values are based on the criteria that 9% air is needed in the mortar phase of the concrete. If the mortar volume will be substantially different from that determined in this recommended practice, it may be desirable to calculate the needed air content by taking 9% of the actual mortar volume.

Water-Cementitious Materials Ratio

A maximum w/cm may already have been established in the mixture design for durability purposes but the w/cm must also be determined for required strength. The final w/cm will be chosen as the lower of the two values. If pertinent strength data is not available, an approximate value for w/cm can be selected from Table 14.28. The strength- w/cm relationships contained in the table are for concrete with a Type I portland cement. For laboratory trials, the w/cm values should be selected to yield an anticipated range of strengths that envelope the average required strength.

Table 14.28 – Approximate Strength-w/cm Ratio Relationships for Non-Air and Air Entrained Concrete (from Table 6.3.4(a), ACI 211.1-99)

Compressive strength at 28 days, psi (MPa)*	Water-cement ratio, by weight	
	Non-air-entrained concrete	Air-entrained concrete
6000 (41MPa)	0.41	--
5000 (35 MPa)	0.48	0.40
4000 (28 MPa)	0.57	0.48
3000 (21 MPa)	0.68	0.59
2000 (14 MPa)	0.82	0.74

* Values are estimated average strengths for concrete containing not more than 2% air for non-air-entrained concrete and 6% total air content for air-entrained concrete. For a constant w/c or w/(c+p), the strength of concrete is reduced as the air content is increased. 28-day strength values may be conservative and may change when various cementitious materials are used. The rate at which the 28-day strength is developed may also change.

Strength is based on 6 x 12 in. cylinders moist-cured for 28 days in accordance with the sections on "Initial Curing g" and "Curing of Cylinders for Checking the Adequacy of Laboratory Mixture Proportions for Strength or as the Basis for Acceptance or for Quality Control" of ASTM method C 31 for moist a f/3.4 ± 3 F (23 ± 1.7 C) prior to testing.

The relationship in this table assumes a nominal maximum aggregate size of about ¾ to 1 in. For a given source of aggregate, strength produced at a given w/c or w/(c+p) will increase as nominal maximum size of aggregate decreases: see Sections 3.4 and 6.3.2.

Throughout this discussion, the water-cement ratio and water-cementitious materials ratio are considered synonymous based on the equivalent weight approach. That is, the weight of cement plus supplementary cementitious materials used is equivalent to the weight of cement if only cement were used. It is recognized that, due to the lower relative density of SCMs, the total volume of cement plus SCM will be slightly greater than the volume occupied if only cement were used.

Cement/Cementitious Materials Contents

Once the water content and the w/cm ratio are known, the cementitious materials content can be calculated. The relative proportions between cement and supplementary cementitious materials should have been determined either in the mixture design or during the selection of specific materials.

Aggregates Proportions

The Absolute Volume method is used here to calculate the volumes of entrapped and entrained air and the constituent materials proportioned to this point. This requires knowledge of the relative densities (specific gravity values) for the constituents. The absolute volume occupied by a material is the weight of the material divided by its relative density and unit weight of water.

Using Experience: For the remaining volume, proportions for coarse and fine aggregates can be based on experience with the local materials. Experience may suggest that a certain weight or volume of coarse aggregates is preferred and the fine aggregates would then be proportioned to fill the balance of the volume. Alternatively, experience may indicate that a certain ratio between coarse and fine aggregates is more effective and the aggregates are proportioned accordingly for the remaining volume.

Using ACI 211.1 Aggregates Table for Proportioning: Without any other basis, coarse aggregates can be proportioned using the recommended bulk volume relationships in ACI 211.1 as shown in Table 14.29. The fineness modulus of the fine aggregates is needed for use in this table to select the appropriate bulk volume of the coarse aggregates. The dry-rodded bulk density (unit weight) of the coarse aggregates as determined from ASTM C 29 is needed for calculation of the dry weight proportion of the coarse aggregates.

$$\text{Dry Weight} = \text{Volume} \times 27 \text{ cf} \times \text{Bulk Density}$$

The fine aggregate is then proportioned to fill the balance of the volume.

Table 14.29 - Coarse Aggregates Volume per Unit of Volume of Concrete (from Table 6.3.6, ACI 211.1-91)

Nominal maximum size of aggregate, in.	Volume of oven-dry-rodded coarse aggregate* per unit volume of concrete for different fineness moduli of fine aggregate+			
	2.40	2.60	2.80	3.00
⅜	0.50	0.48	0.46	0.44
½	0.59	0.57	0.55	0.53
¾	0.66	0.64	0.62	0.60
1	0.71	0.69	0.67	0.65
1-½	0.75	0.73	0.71	0.69
2	0.78	0.76	0.74	0.72
3	0.82	0.80	0.78	0.76
6	0.87	0.85	0.83	0.81

* *Volumes are based on aggregates in oven-dry-rodded condition as described in ASTM C 29.*
These volumes are selected from empirical relationships to produce concrete with a degree of workability suitable for usual reinforced construction. For less workable concrete, such as required for concrete pavement construction, they may be increased about 10%. For more workable concrete see Section 6.3.6.1

\+ *See ASTM C 1.36 for calculation of fineness modulus.*

Optimized Grading: Another approach to proportioning aggregates is to determine an "optimized" blend of aggregates to provide well-graded aggregates composite. This approach is based on the premise that well-graded aggregates has less void space between aggregates particles and thus requires less cement paste. Discussion and optional procedures of this approach are detailed in numerous documents including ACI 302.1R and in FHWA Publication No. HIF-07-004.

Often, the traditional two component aggregates for concrete, coarse and fine, are inadequate in achieving an optimized blend. ACI 302.1R-04 states:

> "To maximize the uniform gradation distribution of the combined aggregates, blending of three or more individual aggregates may be necessary. Generally, this includes one coarse aggregates, one fine aggregates and the addition of an intermediate-size aggregates, typically to compensate for deficiencies in particles' sizes retained on the ⅜-inch (9.5 mm) through No. 8 (2.36 mm) size sieves. There are times when the addition of a second fine aggregates source is necessary to supplement deficiencies in the finer aggregates particle sizes."

Common procedures for aiding in the optimization of the composite aggregates grading include:
- The Percent of Aggregate Retained on Each Sieve (PARS);
- The Coarseness Factor Chart (CFC); and
- The 0.45 Power Chart.

Frequently, two or more procedures are used for a balanced approach to the evaluation.

Percent of Aggregates Retained on Each Sieve provides upper and lower limits for the percent of particles retained on individual sieves for the aggregates composite. For aggregate composites with 1.5 inches (37.5 mm) or greater maximum-size aggregates, the amount of particles retained on each sieve below the nominal maximum size sieve and above the No. 30 (600 μm) sieve should be between 8 and 18 percent. For 1- or ¾-inch (25 or 19 mm) maximum size aggregates, the recommended limits for these individual sieves are 8 to 22 percent. Typically, 0 to 4 percent retained on the nominal maximum size sieve is recommended. For the No. 30 and 50 (600 and 300 μm) sieves, 8 to 15 percent retained on each sieve is commonly accepted as the ideal range as is 1.5 to 5.0 percent for the No. 100 (150 μm) sieve.

The limits of 8 to 18 percent or 22 percent for amounts retained on the No. 4 to 16 (4.75 to 1.18 mm) sieves are applicable when the particles in that size range are round or cubically shaped. The individual percent retained limits should be lowered on these sieve sizes when the aggregates particles are flat and/or elongated. The above recommendations for the percent of aggregates retained on each sieve should only be considered as a guide since aggregates with all of the necessary amounts of particle sizes may not be locally available.

Coarseness Factor Chart is based on the comparative relationship between two factors, Coarseness Factor (CF) and Workability factor (W), and is illustrated in Figure 14.9. The CF is the amount of aggregates retained on the ⅜-inch (9.5 mm) sieve as a percentage of the total amount of aggregates retained on the No. 8 (2.36 mm) sieve. It is determined by dividing the cumulative percent retained on the ⅜-inch (9.5 mm) sieve divided by the cumulative percent retained on the No. 8 (2.36 mm) sieve and expressed as a percentage. The W for a concrete mixture containing 564 pcy (335 kg/m^3) of cementitious material is the cumulative percent of aggregates passing the No. 8 (2.36 mm) sieve. For mixtures with a different cementitious material content, the W is increased or decreased accordingly by a 2.5 value for every 94 pcy (56 kg/m^3) difference in cementitious content from the 564 pcy (335 kg/m^3) base value.

The goal of the procedure is to proportion an aggregates structure for a concrete mixture such that the plot of CF and W falls within the appropriate optimal zone. Zone II is for mixtures with a nominal maximum aggregate size from ¾ inch (19 mm) up to and including 2 inches (50 mm). Zone III is for mixtures with a nominal maximum aggregate size of ½ inch (12.5 mm) or less.

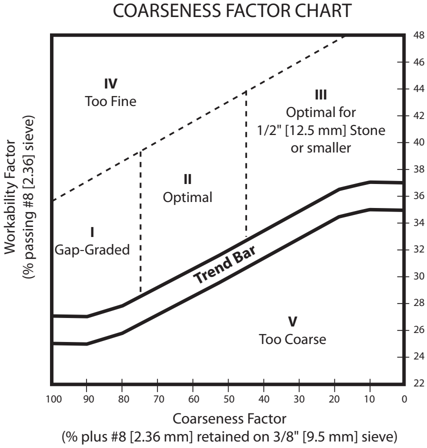


Figure 14.9 Coarseness Factor Chart (from Figure 6.1, ACI 302.1R – 04)

The 0.45 Power Chart was introduced in the United States in the early 1960s by the U.S. Bureau of Public Roads. It historically has been used for evaluating combined gradations in asphalt mixtures but has become a tool for aggregates gradings in concrete also. As illustrated in Figure 14.9, grading values for accumulative percent passing are plotted on the vertical axis and the particle or sieve sizes (in millimeters) raised to the 0.45 power are plotted on the horizontal axis. In the conventional chart, the maximum density grading is represented by a straight line from the origin at the lower left of the chart to the intersection of the desired maximum particle size and the 100 percent passing line. For concrete mixtures, the optimum density line has a bend at the No. 8 (2.36 mm) sieve as shown in Figure 14.9. This chart should only be used as an aid in evaluating composite gradings. Preferred gradations generally plot parallel and close to the optimum line. Grading plots that deviate from this line or that cross the line usually indicate areas of gaps in the aggregates grading.

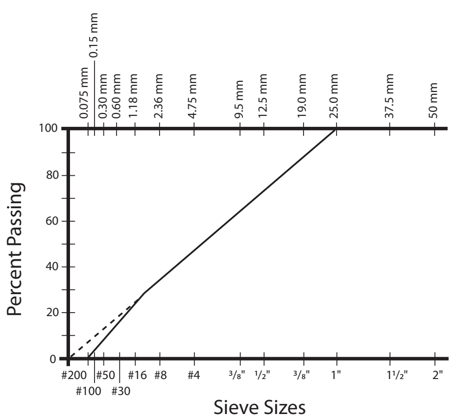


Figure 14.10 Power Chart for an Aggregates with 100 Percent Passing the 1-inch (25 mm) Sieve (from Figure 6.3, FHWA Publication No. HIF-07-004)

14.9 Uses of Portland Cement Concrete

Most concrete used in the United States today is produced in ready-mix concrete plants and delivered by mixing trucks to the site where it is to be used. Ready-mix plants can produce a variety of mixes to suit customer requirements. Typically 35 percent of ready-mix concrete is for single family residential building construction while approximately another 30 percent is for multi-family residential, commercial and public buildings. A major portion of ready-mix concrete that is produced can be considered conventional concrete — concrete with 3 to 5 inch (75 to 125 mm) slump, 3000 to 5000 psi (21 to 35 MPa) compressive strength, and normal durability characteristics. Uses include foundations, piers, basements, beams, columns, slabs, walls, sidewalks, curb and gutter, etc.

On the other hand, precast and prestressed concrete plants produce products such as concrete pipe, cladding panels, concrete block and structural beams. These plants produce their own specialized concrete mixtures which are not available from a ready-mix concrete plant. Even in ready mix concrete there is a growing need for types and uses of concrete that are not so conventional.

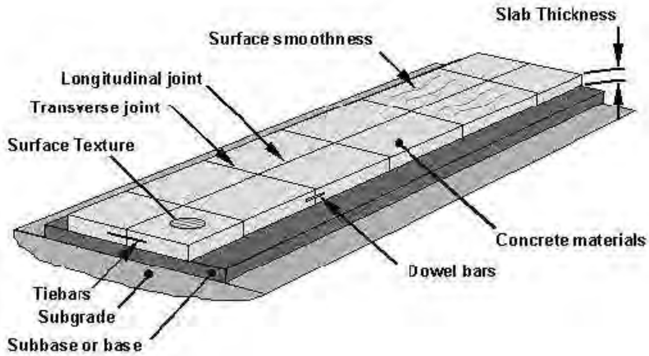
Portland Cement Concrete Pavement

Of the hundreds of millions of cubic yards of ready-mix concrete produced annually in the United States, approximately 30 percent is used in the paving of concrete streets and highways. Additional concrete is used in pavements for airfields, and other public and military uses. The durability and strength of a concrete pavement are particularly important since the surface is exposed to both environmental and loading stresses. Concrete pavement surfaces are exposed to cycles of wetting and drying as well as freezing and thawing. Often salts are applied to the surface to promote snow and ice removal which increases the severity of these cycles.

The most important concrete strength property for pavements is flexural strength. As compared to reinforced structural concrete, concrete pavements do not utilize separate tension reinforcement. Instead, concrete pavements depend on the inherent flexural strength of the concrete itself to resist the bending stresses from traffic loadings. Typical design values for concrete flexural strength range from 500 to 700 psi (3.4 to 4.8 MPa). The required concrete flexural strength for a particular application is obtained through a proper mix design and selection of component materials.

Concrete pavement is considered a "rigid" pavement. As such, the stresses from the applied loads are distributed through the pavement section over a large area of the underlying support material and the unit stress imparted to this support material is lower than from a flexible pavement. Hence, the underlying material does not need to provide necessarily strong support but it does need to provide reasonably uniform support. Otherwise load-induced cracking will occur.

A typical concrete pavement section consists of a prepared subgrade, a subbase and the concrete pavement (Fig. 14.11). The subbase material may be untreated aggregates, asphalt or cement treated aggregates, cement-modified soil, asphalt or econocrete (also referred to as low-strength or lean concrete). Econocrete is concrete with a low content of cementitious material and natural or reclaimed aggregates. Required compressive strength can be up to 1200 psi (8.3 MPa) at 28 days.



American Concrete Paving Association website

Figure 14.11 Schematic of a Typical Concrete Pavement

Concrete pavements are constructed one of two ways. The concrete can be conventionally placed between fixed-forms and then consolidated and struck off with a vibratory screed, a revolving tube or form-riding "bridge deck" machine. Concrete slump for this type of construction is generally not over 3 to 3.5 inches (75 to 87.5 mm). Concrete also can be placed with a slip-form paver through which the concrete is extruded into place. Slump for this methodology rarely exceeds 2 inches (50 mm).

High Performance Concrete

In a Federal Highway Administration special report, *High-Performance Concrete: Understanding the Basics*, high-performance concrete is defined as:

> "...a concrete: made with appropriate materials combined according to a selected mix design; properly mixed, transported, placed, consolidated and cured so that the resulting concrete will give *excellent performance* in the structure in which it is placed, in the environment to which it is exposed and with the loads to which it will be subject for its design life."

The key phrase is "excellent performance." High-performance concrete (HPC) is not a single product but title for concrete mixtures that are developed for specific applications and environmental conditions with a goal of excellent performance. The fresh and hardened properties of HPC exceed those of conventional concrete. Specifications for HPC should not be prescriptive but rather performance-based thus requiring performance testing of the HPC to verify compliance.

In the United States, HPC often has been associated with bridge decks and resistance to chloride penetration and rebar corrosion. In reality, HPC also has been used in many other applications including tunnels, pavements, highrise buildings and parking garages. Table 14.30 lists some of the individual properties and possible specification criteria that may be required of HPC mixtures. No individual HPC mixture will achieve all these properties and a specification should not have requirements for a mixture to meet all the criteria.

Table 14.30 Selected Properties of High-Performance Concrete (from Table 17-2, PCA DCCM)

Property	Test method	Criteria that may be specified
High strength	ASTM C 39 (AASHTO T 22)	70 to 140 MPa (10,000 to 20,000 psi) at 28 to 91 days
High-early compressive strength	ASTM C 39 (AASHTO T 22)	20 to 28 MPa (3000 to 4000 psi) at 3 to 12 hours or 1 to 3 days
High-early flexural strength	ASTM C 78 (AASHTO T 97)	2 to 4 MPa (300 to 600 psi) at 3 to 12 hours or 1 to 3 days
Abrasion resistance	ASTM C 944	0 to 1 mm (0.04 in.) depth of wear
Low permeability	ASTM C 1202 (AASHTO T 277)	500 to 2000 coulombs
Chloride penetration	AASHTO T 259 & T 260	Less than 0.07% Cl at 6 months
High resistivity	ASTM G 59	
Low absorption	ASTM C 642	2% to 5%
Low diffusion coefficient	Wood, Wilson and Leek (1989) Test under development by ASTM	1000 x 10^{-13} m/s
Resistance to chemical attack	Expose concrete to saturated solution in wet/dry environment	No deterioration after 1 year
Sulfate attack	ASTM C 1012	0.10% max. expansion at 6 months for moderate sulfate exposures or 0.5% max. expansion at 6 months fir severe sulfate exposure
High modulus of elasticity	ASTM C 469	More than 40 GPa (5.8 million psi) (Aitcin 1998)
High resistance to freezing and thawing damage	ASTM C 666, Procedure A	Durability factor of 95 to 100 at 300 to 1000 cycles (max. mass loss or expansion can also be specified)
High resistance to deicer scaling	ASTM C 672	Scale rating of 0 to 1 or mass loss of 0 to 0.5 kg/m^3 after 50 to 300 cycles
Low shrinkage	ASTM C 157	Less than 400 millionths (Aitcin 1998)
Low creep	ASTM C 512	Less than normal concrete

Typical HPC mixtures have a high cementitious material content, a water-cementitious materials ratio of 0.20 to 0.40 and an optimized aggregate structure. They also typically contain high-range water-reducing admixtures. HPC mixtures normally contain more than one cementitious material whether it is a blended cement or portland cement with one or two other supplemental cementing materials.

The initial cost for HPC may be as much as double that for conventional concrete. However, HPC structures have lower life-cycle costs than conventional construction because of its enhanced durability and extended service life. Some structures are being designed for a service life of up to 100 years.

Self-Consolidating Concrete

Self-consolidating concrete (SCC) is able to flow in and around reinforcement and into spaces of almost any size and shape and consolidate under its own weight without additional effort, and without segregation and bleeding. Hence, SCC is very beneficial for concrete members that have heavy reinforcement or complicated formwork. In addition, SCC normally produces a very good surface finish with little or no "bugholes" which makes it particularly favorable for architectural precast and cast-in-place concrete. Because self-consolidating concrete is so highly flowable, formwork must be designed or evaluated to assure it can withstand the lateral fluid pressure of the concrete. Another common name for SCC is self-compacting concrete.

In making self-consolidating concrete, it is critical to have a mortar that is very flowable yet has a viscosity high enough to "float" or support the coarse aggregate and thus resist segregation. The water content of the mixture must stay relatively low so flowability is achieved with high-range water reducing admixtures or superplasticizers. The needed viscosity for segregation resistance can be achieved with increased fines content (increased cementitious material content or incorporation of mineral filler) and/or the addition of a viscosity modifying admixture. Normally SCC is produced with smaller size coarse aggregates. Compared to conventional concrete mixtures, SCC normally has a higher paste volume and higher ratio of sand-to-total aggregates. The strength and durability of quality SCC are relatively comparable to conventional concrete. SCC has a higher tendency for plastic shrinkage cracking than conventional concrete and thus timely and proper curing are very important.

Because of the unique nature of SCC, there are different and varied tests for measuring the important characteristics of the fresh mixture. Included in those tests are ASTM C 1610, C 1611, and C 1621. ASTM C 1610 provides a measure of the cohesiveness of the fresh mixture by determining the static segregation of coarse aggregates in a vertical cylindrical specimen.

ASTM C 1611 is the slump flow procedure and provides a measure of the unconfined flow potential of the mixture. It utilizes a standard slump cone (ASTM C 143) but, instead of measuring the vertical slump of the concrete, the diameter of the horizontal flow or spread is measured. An indication of the mixture's relative viscosity can be determined with this procedure by measuring the amount of time it takes for the mixture to flow to a set diameter. With this procedure, a visual, qualitative assessment also can be made of the SCC's stability (resistance to segregation and bleeding).

ASTM C 1621 is a procedure for determining the passing ability or resistance to blocking of self-consolidating concrete mixtures. Passing ability is the ability of the material to not be blocked but to flow around and behind obstructions such as reinforcement. The procedure is the same as the slump flow test but obstructions to the SCC flow are added using a J-ring, a 12-inch (300 mm) diameter ring with circular rods attached. A difference between the slump flow and J-Ring flow of 1 inch (25 mm) or less is an indication of good passing ability. A difference greater than 2 inches (50 mm) indicates poor passing ability.

ICAR research has shown that very good SCC can be made using manufactured sand. A proportioning method has been recommended to assure the correct amount of paste is used to provide adequate workability.

Roller Compacted Concrete

Roller Compacted Concrete (RCC) is similar to conventional concrete in that it has the same constituents and many of the same hardened properties. It differs from conventional concrete in that has lower cement paste content and thus a very "stiff" consistency. Consolidation is achieved not with internal vibration but by external compaction from rollers whereby it gets its name. RCC primarily has been utilized in the pavements and water resources realms. The Portland Cement Association has numerous publications on RCC for both applications. The primary American Concrete Institute documents for RCC are ACI 207.5 on roller compacted mass concrete for water control structures and ACI 325.10 on roller compacted concrete pavements.

RCC is used for most any type of industrial or heavy-duty pavements such as at port facilities, intermodal yards and military facilities. There is widespread use of it in parking and storage areas and it also has been placed in streets, intersections, low-speed roads and even interstate shoulders. For pavements, RCC is normally placed with conventional or high-density asphalt paving equipment and then rolled thus alleviating the need for forms and finishing. RCC paving is constructed without dowels or steel reinforcing and typically without joints. Nominal maximum aggregates size can be up to 1.5 inches (37.5 mm) but, for smoother surfaces, ¾ inch (19 mm) is the norm.

RCC is well-suited for use in water resources' structures such as dams, emergency spillways, stilling basins, channel lining and grade-control structures. For these applications, RCC is normally placed with earth-moving equipment including bulldozers, motor graders, spreader boxes and even paving machines. In most applications, RCC is placed in multiple horizontal lifts with stair-stepped tapered edges as shown in Figure 14.12. Each lift of RCC is usually up to 1 foot (300 mm) in thickness. Maximum aggregates size can range up to 6 inches (150 mm). Because the aggregate structure provides immediate density and stability after compaction, a freshly placed and compacted layer of RCC can immediately support the equipment for placement of the next layer.

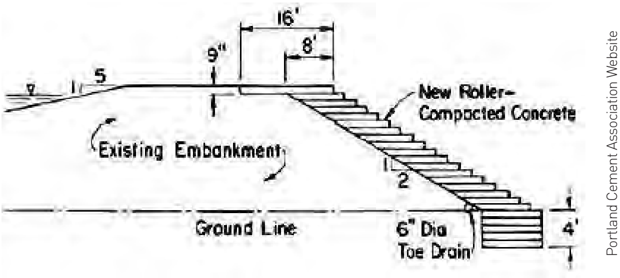


Figure 14.12 Example of Roller Compacted Concrete Stair Stepped Construction

Because of the very dry, stiff nature of fresh RCC, testing and strength specimen molding is different from those for conventional concrete. Appropriate water content and workability for paving mixtures often is determined from common soil moisture-density testing methods such as ASTM D 1557. Compressive strength specimens can be molded using the same techniques for density determination or molded in cylinders using a vibrating hammer, ASTM C 1435.

For water resource applications, optimum water content/maximum density often is determined by the specific behavior of a RCC sample under a surcharge weight subjected to vibration from a "Vebe" table, ASTM C 1170. This same vibrating table also can be used in the molding of compressive strength specimens following the method of ASTM C 1176. Otherwise, the vibrating hammer of C 1435 is the common method for molding compressive strength specimens.

Pervious Concrete

As its name implies, pervious concrete has a high permeability which allows water to easily pass through it. It can be used in many applications but most often is used in pavements where there is a desire to minimize runoff yet rapidly shed surface water. It can have the added benefit of recharging the local groundwater. Flow rates can range from 2 to 18 gallons per minute per square foot (81 to727 liters per minute per square meter).

Pervious concrete mixtures are similar to conventional concrete in that they contain the common ingredients of cementitious materials, coarse aggregates and water. They differ from conventional concrete in that they have only a small amount of fine aggregates or no fine aggregates at all and there is just enough cementitious paste to coat the coarse aggregates particles. Hence, the hardened mixture is primarily held together by cementitious paste at the contact points of the coarse aggregates particles leaving 15 to 30 percent of interconnected void space in the concrete.

Chemical admixtures are commonly included in the mixture and water-cementitious materials ratios can range from 0.27 to as high as 0.45. The mass of aggregate is commonly 4 to 4.5 times that of the cementitious material. Higher strength and durability usually is achieved with lower ratios of water to cementitious material and aggregates to cementitious material. The appropriate water content is crucial to pervious concrete mixtures. Excessive water content leads to segregation and cementitious paste dripping off aggregates particles. Inadequate water content leads to balling of the fresh material in mixing and premature drying before adequate curing can be applied to the concrete. This in turn leads to a weaker material that is prone to surface raveling. The same result will occur if there is inadequate curing, even if the initial water content is correct.

For paving applications, pervious concrete can be placed into fixed forms and struck off by manual or vibratory screeds or it can be extruded through a slip-form paver. On larger jobs, the surface should be compacted with conventional paving rollers immediately after placement and strike-off. For smaller jobs with thinner pavement sections, consolidation can be achieved with vibratory screeds or hand rollers. No other finishing procedures such as troweling are applied to pervious pavement surfaces so that they remain open and thus ensure permeability.

Pervious concrete is not generally based on strength. Normal compressive strengths range from 500 to 1500 psi (3.4 to 10.3 MPa) but mixtures can be designed for strengths up to 4000 psi (28 MPa). Because permeability and void content are so critical, acceptance of pervious concrete is usually predicated on density as measured by the jigging method of ASTM C 29.

Recycled Concrete

Recycled concrete is merely old concrete that has been broken up and removed from its original use, had reinforcing and other embedded items extracted, and then been crushed to produce aggregate. Depending upon end use, the resulting aggregates may be further processed by screening into fine and coarse aggregates components. Recycled concrete has many uses throughout the various construction sectors but a large majority has been in transportation projects. A 2007 FHWA study revealed that 38 states used recycled concrete as an aggregates base and 11 utilized it into new portland cement concrete.

As a component in new concrete, recycled concrete aggregates can be a partial or total replacement of the coarse aggregates and can be a partial replacement of the fine aggregates. Recycled aggregates should be tested for the key properties as required of a conventional aggregate. Normally, only recycled aggregates crushed from very poor quality concrete fail to meet the properties requirements. In addition to the standard aggregates testing, it is prudent to check for the sulfate and the chloride contents of the recycled aggregates as well as its potential expansion characteristics from alkali silica reactivity.

There are distinct factors related to the use of recycled concrete as aggregates in new concrete that should be considered. The relative density (specific gravity) of recycled concrete aggregates is lower than conventional aggregates and thus concrete density will be less. Also, absorption is higher in recycled concrete aggregates as compared to conventional aggregates with values ranging from 3 to 10 percent. Absorption is greatest in the fine aggregates particles and least in the larger coarse aggregates particles. The higher absorption will require more total mix water and, similar to lightweight aggregates, the stockpiled material should be pre-wetted prior to concrete production to avoid slump loss problems.

For concrete made with all natural fine aggregates and up to 30 percent recycled aggregates, there is no significant effect on its hardened properties. There is an increase in drying shrinkage with higher amounts of recycled coarse aggregates yet little impact to the strength and durability. There can be a significant impact on concrete properties when recycled fine aggregates are utilized in concrete. As recycled fine aggregates content is increased, the fresh concrete mix becomes more harsh and unworkable and the hardened concrete has reduced strength and significantly increased drying shrinkage and creep. Recycled fine aggregates content above 20 percent is generally considered unfavorable.

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Chapter 15

Effect of Aggregates on the Characteristics and Performance of Hot Mix Asphalt

Dallas N. Little

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15.1 Types of Asphalt Pavements

Hot Mix Asphalt

Hot mix asphalt (HMA) or asphalt concrete consists of a combination of aggregates that are uniformly mixed and coated with asphalt cement. To dry the aggregates and obtain sufficient fluidity of asphalt cement for proper mixing and workability, both the aggregates and asphalt are heated before mixing. There are three generally accepted forms of HMA.

Dense graded HMA mixtures: Dense graded HMA mixture uses a well-graded aggregates gradation to produce a dense HMA mixture.

Stone matrix asphalt: A stone matrix asphalt (SMA) mix is an HMA mixture that uses a gap graded aggregates gradation to produce stone-on-stone contact with high asphalt contents to improve durability. In general, SMA uses a polymer modified asphalt and in most instances fiber additives as a stabilizer. It produces a densely compacted asphalt pavement-wearing surface with very high resistance to permanent deformation.

Open-graded: An open-graded HMA mixture designed to have a large volume of air voids so that water will drain through the pavement layer. It uses a single size aggregates that consists of particle size. It is used as an open-graded friction course (OGFC) to provide a skid resistant pavement surface and as a porous base layer to provide for positive drainage under either a HMA or portland cement concrete pavement surface

Surface Treatments

Surface treatments involve spreading a high-quality crushed aggregates on a base or existing pavement surface that already has received a spray application of asphalt material. The asphalt material provides a waterproofing membrane over the existing surface and bonds the aggregates in place to form a new riding surface. Aggregates are spread at a prescribed rate and is embedded in the asphalt by rolling. This aggregates forms a wearing surface. Surface treatment aggregates should be clean, predominately one size, cubical or pyramidal in shape and have an affinity for asphalt. Aggregates that are weak and unsound or includes deleterious material that breaks down under environmental effects such as freezing and thawing or wetting and drying is undesirable. There are two common types of surface treatments using aggregates: chip seals and slurry seals.

Chip Seals: A chip seal consists of single or multiple applications of a uniformly graded cover aggregates placed over an aggregates base or existing pavement. A spray application of asphalt is required for each aggregates application. A chip seal involves a single layer of aggregates that is embedded in a film of asphalt. A sufficient amount of aggregates are spread so that particles are close together. Many times multiple chip seals are placed. A double chip seal will consist of an application of asphalt followed by the spreading of the aggregates. It is then followed by another application of asphalt and aggregates. The aggregates for the second chip seal will be approximately one half the size as the aggregates in the first chip seal. For example, a first layer using ¾-inch aggregates would be followed by a second layer using ⅜-inch aggregates.

Slurry Seals: A slurry seal is a designed mixture of well-graded fine aggregates, mineral filler (if needed), emulsified asphalt and water applied to a pavement as a surface treatment. It is used in both the preventive and corrective maintenance of asphalt pavement surfaces. It does not increase the structural strength of a pavement section.

15.2 Aggregates Properties for Hot Mix Asphalt

Asphalt-aggregates mixtures have, depending upon the application, varying aggregates requirements for gradation, particle shape, soundness, abrasion resistance, unit weight, plastic fines and polish values. The aggregates component used in asphalt mixtures is selected by optimizing quality and economy. Important aggregates properties for these applications along with appropriate tests are summarized in Chapter 3.

Gradation

The grading or gradation of aggregates is the distribution of the various particle sizes. Gradation is typically determined by both a washed-sieve analysis and a dry-sieve analysis. ASTM C-136 (AASHTO T-27) is the procedure for dry sieving. In this procedure, the mass of a sample of dry aggregates is determined and then the sample is passed through a series of sieves with progressively smaller openings. Once separated, the mass of material retained on each sieve is measured and compared to the total sample weight. The aggregates gradation is ultimately expressed as the accumulative percent passing each sieve size. Figure 15.1 shows the typical gradation for a dense-graded HMA mixture, a SMA mixture and an OGFC.

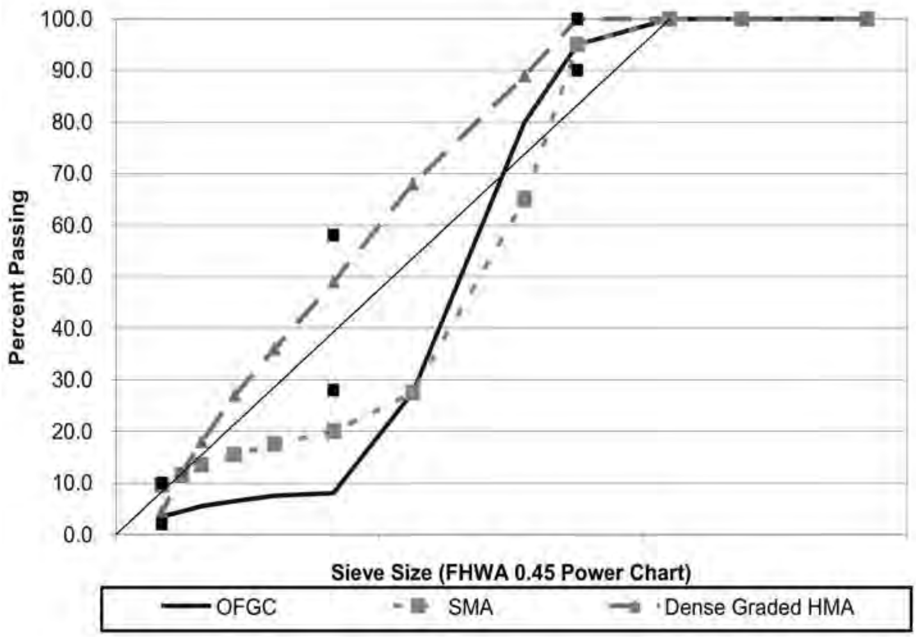

Figure 15.1 Typical Gradation for ½-in (12.5 mm) Dense-Graded HMA, SMA and OGFC

Nominal maximum size. This also is defined in Chapter 3. For Superpave mixes the nominal maximum size is used. The nominal maximum size is defined as one sieve size larger than the first sieve to retain more than 10 percent. The maximum size is one size larger than the nominal maximum size.

Specific Gravity, Absorption and Unit Weight

Specific Gravity: In bituminous applications, the specific gravity of the aggregates is used in calculating the air voids, voids in the mineral aggregates and voids filled. Voids in the mineral aggregates (VMA) are the spaces between the aggregates particles. Voids filled with asphalt (VFA) are the voids occupied by asphalt. The remaining voids not occupied by aggregates or asphalt are air voids (AV). See Figure 15.2. Voids are given as a percent of the total volume of the compacted mixture. Procedures for determining aggregates apparent and bulk specific gravities are given in ASTM C 127 and C 128 for coarse and fine aggregates, respectively. Aggregates apparent specific gravity is based on a unit volume of aggregates not permeable to water. Water will permeate more aggregates voids than asphalt. Aggregates *bulk specific gravity* is based on a unit volume of saturated surface dry aggregates and includes the aggregates voids that are permeable to water. Effective specific gravity is used based on a unit volume of the aggregates permeable to asphalt. The numerical value of effective specific gravity falls between the apparent and bulk specific gravity values.

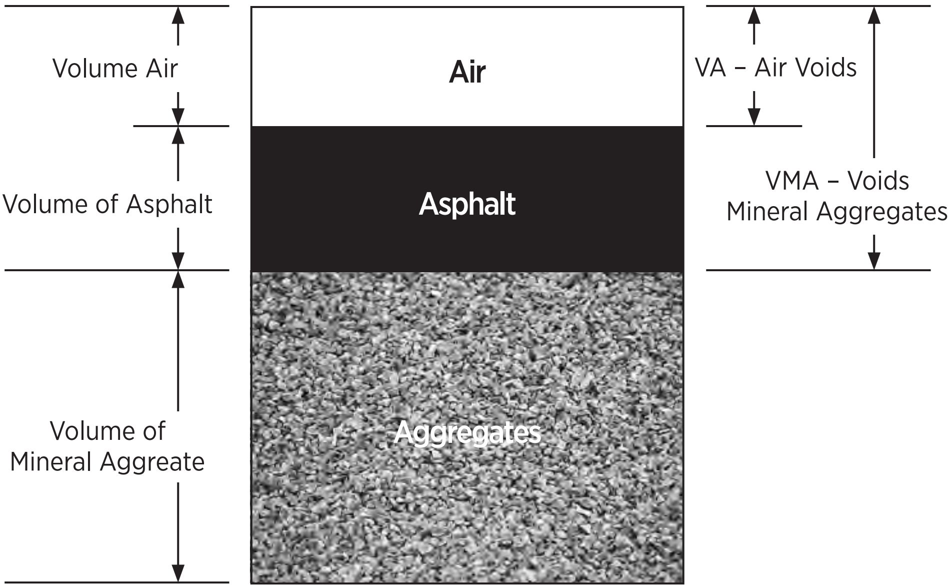

Figure 15.2 Diagram Showing Relationship between Air Voids and Voids Mineral Aggregates

Absorption: The effective specific gravity is used to account for aggregates asphalt absorption. The amount of asphalt absorption determines the effective asphalt content and is important when applying voids criteria. If the asphalt absorption is greater than considered in the mix design, then the bituminous mixture could have low durability. If the asphalt absorption is less than considered, then the mixture could have excess asphalt and be unstable. Absorption can refer to either asphalt absorption or water absorption. Water absorption is an indicator of asphalt absorption. Both water and asphalt are absorbed by most aggregates. However, aggregates with water absorption values greater than 2 to 2.5 percent are considered absorptive. Water absorption also indicates the aggregates may be difficult to dry. In mixing, moisture retained by absorptive aggregate restricts effective coating.

Unit Weight: Aggregates unit weight is not important in proportioning HMA mixtures. However, aggregates unit weight affects yield of end product and therefore the cost of the finished work. Asphalt content is based on the percent of the total weight of the mix.

Toughness and Abrasion

Mineral aggregates toughness and abrasion resistance is important to the performance of an HMA mixture. The aggregates, once sized, must resist further size reduction in subsequent processing, mix production and construction. Aggregates toughness also is desired to resist in service breakage from intense surface traffic loadings and point-to-point contact stresses. Degradation due to processing in mix production contributes to aggregates size reduction. However, the fines generated by degradation are more important in performance of the HMA mixture than the reduction in aggregates size. Fines contribute to excess mineral filler and affect the overall gradation and asphalt characteristics. Fines also coat larger aggregates and reduce the asphalt-aggregates bond.

Los Angeles Degradation Test: The Los Angeles (L.A.) Degradation Test commonly is used in an attempt to restrict degradable aggregates in both PCC and HMA mixes. L.A. degradation requirements vary for aggregates used in asphalt mixtures depending on the anticipated severity of performance conditions. Aggregates having lower L.A. degradation values is specified for layers near the surface and subject to high stresses. A uniformly graded aggregates (i.e., aggregates having a small variation in particle size) has more point-to-point contact with higher stresses and therefore requires lower L.A. degradation values. Acceptable L.A. degradation values specified by various agencies for HMA usually are based on local experience and upon the availability of high-quality aggregates. Limestone having L.A. degradation values of less than 40 are considered to represent good, tough and abrasion-resistant aggregates, but such aggregates are not always available. For SMA mixtures the L.A. degradation value is many times lower than for dense-graded HMA mixtures. The L.A. degradation scale is not linear nor consistent from one rock type to another. Many limestones create dust during the L.A. degradation test. This dust restricts the breaking of aggregate and, as a result, gives deceptively low abrasion values. Granitic rocks are composed of minerals that are hard and brittle. They tend to yield high losses in the L.A. test but usually perform well in service.

Particle Shape and Texture

Particle Shape: In an HMA mixture cubical aggregates provide greater interlock and internal friction. This results in an HMA mixture with higher stability than rounded aggregates.

Flat and elongated particles used in asphalt applications tend to increase mixture voids and affect compactability. Compaction is important because achieving high density in an HMA mixture enhances its strength, stability, resistance to stripping, raveling resistance and reduces asphalt hardening. Also, compaction obtained during construction and from subsequent traffic can cause flat and elongated particles to fracture or take a preferred orientation. Aggregates fractured in this manner have an uncoated surface and is more susceptible to the detrimental influence of infiltrating water. Particle reorientation can cause a loss of skid resistance in surface applications. Also, as particles realign, the void structure changes. A reduction in the VMA, which might gradually occur over a period of time, can cause the existing asphalt content to become excessive. As a result, instability problems develop in the mix or the excess asphalt flushes to the surface causing a loss of skid resistance. Some rock types tend to break during crushing operations giving a high percentage of flat and elongated particles. A proper choice of crushing equipment can reduce the amount of flat and elongated particles produced, as discussed in Chapter 9. Flat and elongated particles should be limited to 10 percent of the total aggregates. This limit on flat and elongated particles is used in specifications by a number of agencies. Flat and elongated particles may be compensated to some extent by experience through adjustments in the mix design. They should not be used in surface treatment applications.

Texture: The surface texture of the aggregates affects the workability and strength of an HMA mixture. A rough, sandpaper-like surface texture found on crushed stone will increase the strength. It also will require additional asphalt binder to provide good workability. Voids in a compacted HMA mixture using rough surface textured aggregates usually will being higher than smooth aggregates obtained from river gravels and sands. Smooth textured aggregates usually will be easier to coat than aggregates with high surface texture, but the asphalt binder usually forms stronger mechanical bonds with rough-textured aggregates.

Durability

Sulfate Soundness Tests: Aggregates that are satisfactory for use as concrete aggregates usually are also suitable for HMA applications. Asphalt cement binder is not chemically reactive and provides some waterproofing as long as the aggregate coating remains intact. Numerous agencies specify soundness tests to qualify aggregates for use in HMA applications. Both magnesium and sodium sulfate soundness tests are utilized, with limits on the test results often being based on local experience. Typical maximum total weighted percentage losses given by ASTM D 692 for coarse aggregates after five cycles of immersion in a saturated solution of sodium or magnesium sulfate followed by oven drying are 12 and 18 percent, respectively. The corresponding maximum losses given by ASTM D 1073 for fine aggregates after five cycles are 15 and 20 percent, respectively.

Aggregate Expansion: Aggregates utilized for asphalt mixtures are subject to the same stresses from freezing and thawing as those utilized in portland cement concrete. The volume expansion of water when undergoing freezing exerts internal pressures in voids or weakness planes of the aggregates which can result in fracture of the aggregates. When this occurs in asphalt concrete or in untreated stone used as cover stone for surface treatments, the asphalt-aggregates bond is reduced and a loss of performance occurs. The asphalt, which has viscoelastic characteristics and fully coats the aggregates in an asphalt concrete mix, limits the severity of any popouts if they occur at all. Sources of such nondurable aggregates usually are identified by using agencies and limits are placed on their use. An asphalt concrete surface exhibiting aggregates freeze-thaw damage is pock-marked in appearance. Close examination of this surface usually reveals individual aggregates deterioration. Aggregates located beneath a surface that has freeze-thaw damage causes a slight heave that may not easily be detected and is compacted by traffic in warmer weather.

Deleterious Materials, Organic Impurities and Clay Balls

Materials that restrict asphalt from coating aggregates particles, react with the environment or do not consist of mineral matter are detrimental to HMA applications. Excess mineral filler, silt and clay all coat the aggregates and affect the bond between the asphalt and aggregates. Clay absorbs moisture and can accentuate loss of asphalt coating on the aggregates. With warm temperatures, moisture and traffic, clay can contribute to emulsification of the asphalt. When that happens, the asphalt no longer is an effective binder. Clay, as well as other fines, can absorb enough moisture to cause the asphalt mixture to swell. In some cases, clay balls form during preparation of the HMA mixture and become coated with asphalt. Subsequently, the encapsulated clay ball disintegrates when it becomes wet. Metal oxides present in aggregates sources react with moisture causing localized swelling leading to pop-outs and staining of the pavement surface. Roots, sticks and other contamination absorb moisture or otherwise react with environmental factors and contribute to HMA mixture deterioration.

Polishing: Aggregates that polishes under traffic are a problem in asphalt surface applications. The Asphaltic mastic that encapsulates the coarse aggregates contributes significantly to skid resistance. The coarse aggregates, however, ultimately is exposed and determines the skid resistance. Hard, durable aggregates provides desirable skid-resistance characteristics.

Mineral Filler: In addition to performing degradation and soundness tests on the coarse and fine aggregates, the mineral filler should be tested for plasticity. The *plasticity index*, which is the difference in the Atterberg liquid limit and plastic limit moisture contents, and the sand equivalence both indicate the presence of undesirable mineral filler. The maximum allowed plasticity index given in ASTM D 3515 is four for mineral filler used for HMA mixtures. *Sand equivalency* is a measure of the clay-like or plastic fines in granular soils and fine aggregate. The test (ASTM D 2419) is conducted on the minus No. 4 sieve size material. A typical minimum sand equivalency for aggregates used in hot mix asphalt concrete varies from 45 to 50.

The amount and type of mineral filler added to the aggregates in an HMA mix is important. Mineral filler should be accounted for as an increment of the overall aggregates gradation. In HMA mixtures an optimum amount of mineral filler is needed to achieve maximum density. However, mineral filler can coat larger aggregates particles and affect the asphalt-aggregates bond. In addition, because of its small particle size, mineral filler can become incorporated into the asphalt film. The mineral filler stiffens the asphalt and increases its volume. A stiffer asphalt contributes to mix stability in warm weather, but can lose flexibility and crack in cold weather. Bulking of the asphalt because of excess mineral filler increases its effective volume and can cause instability of the mix from overfilling of its voids. A ratio of mineral filler to asphalt content of about 0.6 to 1.5 for dense HMA mixtures typically is used. SMA mixtures require additional mineral filler to stabilize the mix. Therefore, in many cases as much as 10 percent mineral filler is added to an SSMA mixture. It is important that the quality and quantity of mineral filler be determined and controlled. Quality can vary substantially in plants that blend materials to arrive at a final gradation. Natural, unwashed sands and gravels frequently are coated with clay and silt, neither of which is desirable in asphalt concrete. Excessive quantities of mica in crushed stone fines are equally undesirable. Mineral filler should be evaluated prior to acceptance in finished mixtures.

Aggregate Surface Chemistry: Surface chemistry determines whether aggregates are hydrophobic or hydrophilic, and also plays an important role in determining the type of asphalt that should be utilized with the aggregates. The term *hydrophobic* means water hating and *hydrophilic* means water loving. Hydrophobic aggregates have a preference for wetting by asphalt as opposed to water. Hydrophilic aggregates prefer water over asphalt. *Hydrophilic aggregates attract moisture to its surface, which can even displace a previously established asphalt coating.*

The result is one form of stripping, which is the loss of the aggregates asphalt coating. Loss of asphalt coating leads to raveling and flushing of asphalt to the pavement surface, and mixture instability. Aggregates that are basic, such as limestone and dolomite, tends to be hydrophobic. Acidic aggregates, such as granite, rhyolite and siliceous gravel containing chert and quartzite, is hydrophilic.

Hydrophilic characteristics can be at least partially counteracted by the use of up to 2 percent of hydrated lime as a mineral filler fraction or by the addition of commercial anti-stripping additives to the asphalt. Typically 0.5 to 1.5 percent of hydrated lime is used. Methods for evaluating stripping tendencies of aggregates sources are described later in this chapter in the sections covering mix design.

15.3 Bituminous Material

Several types of asphalt materials that serve as binders in connection with aggregates are utilized in pavement applications. Asphalt products are obtained from refining crude oil. Asphalt is the residual product left after lighter fractions of the crude have been removed by distillation. Asphalt is readily available, but varies in cost directly with the value of crude oil.

Asphalts: Asphalts exist naturally as lake or pool deposits, seams of pure, hard asphalt in geological formations and rock asphalt consisting of relatively porous rock, such as sandstone, impregnated with asphalt. Most asphalts today, however, are derived from the fractional distillation of crude petroleum. The origin of petroleum is the result of (1) a chemical reaction, (2) condensation of hydrocarbon gases or (3) the residuum from decaying plant or animal matter. Asphalt is an important constituent of petroleum. As a result, petroleum is classified as asphalt or non-asphalt (paraffinic) depending on the predominance of asphalt from its refining. The relative amounts of the asphalt and non-asphalt components determine the most effective refinery process for a given petroleum.

Asphalt Production: Although asphalts appear to be homogeneous and uniform, they are actually far from it. The properties of asphalts produced from different crude sources can vary substantially. The differences are often minor or can be made relatively minor by processing. However, sometimes the differences are great enough to produce asphalts with different performance characteristics. Asphalt can be produced in the distillation process to its final consistency or grade. In such a process, there is no blending with other asphalts or fluxing with lighter petroleum products. Asphalt cement also is produced by subjecting the petroleum to processes (extreme temperature and/or pressure) that break down the larger molecules (cracking). Refining to obtain asphalt cement also is accomplished by solvent precipitation. Today's technology and the economics of the petrochemical industry dictate that as many petroleum fractions be recovered as possible. Therefore, most asphalt cement available today is not distilled to grade but involves blending, fluxing, air blowing or a combination of these processes to meet the consistency requirements given in specifications.

Asphalt Types

Asphalt Cement: Asphalt cement is the basic form of asphalt as produced by crude oil refining. Asphalt cement is a thermoplastic material that varies in consistency depending upon its source and processing method, and it is a semi-solid at ambient air temperatures. It is liquefied for mixing or spraying by increasing its temperature to about 350º F so as to readily coat aggregate and permit placing and compaction of the asphalt mixture in a pavement structure. Upon cooling, the asphalt cement returns to its semi-solid state and securely holds the aggregate particles in place. Asphalt cement is specified using the Superpave Performance Graded Asphalt Specification.

Many times a modified asphalt is used. They are generically referred to as "polymer modified asphalts" or PMAs. In actuality, though, modified asphalt binders may be produced in a number of ways including polymer and chemical modification, although polymer modification is the most prevalent. When blended into an asphalt, cement polymers can behave in two different ways. If the polymer forms discrete particles in the asphalt binder, then it functions primarily as a thickener, which increases the viscosity of the asphalt binder while having no significant effect on low temperature properties. If the polymer forms a continuous network in the asphalt binder, then it functions as a homogeneous blend, which may impart some of the physical characteristics of the polymer to the asphalt binder. In this instance the high and low temperature properties of the asphalt binder may be affected.

Asphalt Emulsions: Asphalt emulsions are suspensions of either asphalt cement globules in water or water suspended in asphalt. Chemical emulsifying agents are incorporated to maintain stability of the suspension until the appropriate time for "breaking" is reached. An emulsion breaks after exposure due to deterioration of the emulsification agent, which reduces the quantity of water present and allows the asphalt globules to unite into a continuous film of asphalt. Premature breaks occur in the presence of dust and at low temperatures. The emulsions are formulated as slow-, medium- and rapid-setting (breaking) types.

Chemicals utilized for emulsification of asphalt also impart surface charge characteristics to the emulsion. Emulsified asphalts are positively charged (cationic) or negatively charged (anionic) and should be matched with appropriate aggregates to assure proper asphalt-aggregate adhesion. Like charges repel and opposite charges attract, a good residual asphalt coating is achieved by selecting an emulsion having the opposite charge relative to the aggregates surface.

Table 15.1 Emulsified Asphalt Grades

	Anionic	Cationic
Rapid Setting (RS)	RS-1	CRS-1
	RS-2	CRS-2
	HFRS-2	
Medium Setting (MS)	MS-1	
	MS-2	CMS-2
	MS-2h	CMS-2h
	HFMS-1	
	HFMS-2	
	HFMS-2h	
	HFMS-2s	
Slow Setting (SS)	SS-1	CSS-1
	SS-1h	CSS-1h
Quick Setting (QS)	QS-1h	CQS-1h

Asphalt Cutbacks: Asphalt cement also can be liquefied by diluents such as naphtha, kerosene and oil. Combinations of these materials create cutback asphalts designated as rapid curing (RC), medium curing (MC) or slow curing (SC), respectively. Cutback asphalts are utilized at or near ambient air temperatures, but do not attain full strength as a binder until the diluent has evaporated. Cutback asphalt was widely used in prior years as material for prime coats and surface treatments where lengthy working time was required. More recently, the use of cutback asphalt has been restricted because of the hydrocarbon vapors released to the atmosphere during the curing process.

Petroleum solvents used for dissolving asphalt cement are variously called distillate, diluents or cutter stock. If the solvent used in making the cutback asphalt is highly volatile, it will quickly escape by evaporation. Solvents of lower volatility evaporate more slowly. It is based on the relative speed of evaporation, that cutback asphalts are divided into the following three types:

- **Rapid-curing (RC):** asphalt cement combined with a light diluent of high volatility, generally with a boiling point similar to gasoline or naphtha. Grades include: RC-70, RC-250, RC-800 and RC-3000;

- **Medium-curing (MC):** asphalt cement combined with a medium diluent of intermediate volatility, generally with a boiling point similar to kerosene. Grades include: MC-30, MC-70, MC-250, MC-800 and MC-3000;

- **Slow-curing (SC):** asphalt cement combined with oils of low volatility. Grades include: SC-70, SC-250, SC-800 and SC-3000.

Slow-curing (SC) cutback asphalts may also be referred to as road-oils. This term originated in earlier days when asphalt residual oil was used to give roads a low-cost, all weather surface.

The degree of liquidity developed by each cutback asphalt depends principally on the proportion of solvent to asphalt cement. To a minor degree, the liquidity of the cutback may be affected by the hardness of the base asphalt from which the cutback is made. The more viscous grades of cutback asphalt are indicated by higher numbers in the grade designation, and may require a small amount of heating to make them fluid enough for construction operations.

15.4 Dense Graded Hot Mix Asphalt Mixtures

Flexible pavements having a high traffic volume and heavy loads have one or more layers consisting of hot mix asphalt (HMA). HMA concrete is a mixture of aggregates, mineral filler and asphalt. The aggregate used in the mixture consists of either coarse or fine aggregate or more frequently a mixture of both sizes. Paving grade asphalt cement, emulsion or cutback can be used. The aggregates are heated, dried and mixed with heated asphalt. Usually the asphalt concrete used for a pavement is selected and proportioned so that each successive layer above the aggregates base is finer and has a higher asphalt content.

Uses of HMA

HMA mixtures are used for the construction and maintenance of a variety of the following pavement types:
- City streets
- Parking areas, walkways and driveways
- Local and interstate highways
- Airports and airfield pavements
- Storage yards and transfer facilities
- Railroad track structures
- Recreational surfaces

HMA Requirements

HMA should have the following desirable characteristics:
- Workability for ease of placement
- Stability to resist flow and compaction under the applied loading
- Durability when subjected to the service environment
- Fatigue resistance and flexural strength
- Resistance to moisture damage (i.e., stripping resistance)
- Skid resistance

These properties reflect characteristics related to mix design, construction, performance and safety.

Aggregates Properties

There are two major aggregates specifying groups in the United States: the Federal Aviation Administration for airfields and the state Departments of Transportation that provide specifications for highways.

Federal Aviation Administration: The aggregates used for airfield construction are to be crushed stone, crushed gravel or crushed slag with or without natural sand or other inert finely divided mineral aggregates. The portion of materials retained on the No. 4 (4.75 mm) sieve is coarse aggregates. The portion passing the No. 4 (4.75 mm) sieve and retained on the No. 200 (0.075 mm) sieve is fine aggregates and the portion passing the No. 200 (0.075 mm) sieve is mineral filler.

The coarse aggregates must consist of sound, tough, durable particles, free from adherent films of matter that would prevent thorough coating and bonding with the bituminous material and be free from organic matter and other deleterious substances. The percentage of wear shall not be greater than 40 percent when tested in accordance with ASTM C 131. The sodium sulfate soundness loss shall not exceed 10 percent, or the magnesium sulfate soundness loss shall not exceed 13 percent, after five cycles, when tested in accordance with ASTM C 88.

The FAA specifies that the aggregates must be crushed aggregates. They specify the percent by weight of individual pieces having two or more fractured faces and the percent by weight having at least one fractured face based on the weight of the aircraft operating from the airfield being built. The area of each face shall be equal to at least 75 percent of the smallest mid sectional area of the piece. When two fractured faces are contiguous, the angle between the planes of fractures shall be at least 30 degrees to count as two fractured faces. Fractured faces shall be obtained by crushing.

The aggregates shall not contain more than a total of eight percent, by weight, of flat particles, elongated particles and flat and elongated particles, when tested in accordance with ASTM D 4791 with a value of 5:1.

When slag is used it must be air cooled, blast furnace slag and shall have a compacted weight of not less than 70 pounds per cubic foot (1.12 mg/cubic meter) when tested in accordance with ASTM C 29.

The fine aggregates shall consist of clean, sound, durable, angular shaped particles produced by crushing stone, slag or gravel that meets the requirements for wear and soundness specified for coarse aggregates. The aggregates particles must be free from coatings of clay, silt or other objectionable matter and shall contain no clay balls. The fine aggregates, including any blended material for the fine aggregates, shall have a plasticity index of not more than six and a liquid limit of not more than 25 when tested in accordance with ASTM D 4318.

The FAA allows the use of natural (non-manufactured) sand to obtain the gradation of the aggregates blend or to improve the workability of the mix up to a maximum of 15 percent by weight of total aggregates. If used, the natural sand must meet the requirements of ASTM D 1073 and shall have a plasticity index of not more than six and a liquid limit of not more than 25 when tested in accordance with ASTM D 4318.

Superpave

When the Superpave™ design procedure was developed it used existing aggregates properties which were divided into the following categories:

- Consensus Properties
  - Coarse Aggregates Angularity
  - Fine Aggregates Angularity
  - Flat and Elongated Particles
  - Clay Content (Sand Equivalency)
- Source Properties
  - Toughness (L.A. Degradation)
  - Soundness
  - Deleterious Materials

The consensus properties were established by the FHWA as suggested requirements for a Superpave mixture and are properties that can be controlled by the contractor during crushing and screening operations. The source properties are properties of an aggregates source and the suggested values for these properties will vary due to aggregates economically available in each of states. Therefore, the requirements for the source values will reflect the needs of the DOTs.

Coarse and Fine Aggregates Angularity: Increased coarse and fine aggregates angularity increases mixture rutting resistance. As angularity increases, VMA increase, which results in higher binder contents. Higher binder contents contribute to improved durability. The requirements for percentage of crushed faces for coarse and fine aggregates shown in Table 15.2 are based on level of design traffic and depth of the asphalt concrete (AC) layer. In large part, these requirements are given in the Superpave procedure to reduce rutting potential. However, when applied to gravel, the requirements for crushed faces of coarse aggregates are marginal in their ability to limit rutting potential. The requirements on percent crushed faces are superfluous if applied to a crushed rock such as limestone, granite or slag since these materials are angular and do not require further crushing. Rutting is significantly affected by the fine aggregates angularity. Superpave fine aggregates angularity requirements, given in Table 15.2, limits the use of many natural sands.

Flat and Elongated Particles: Superpave limits the amount of aggregates particles, greater than 4.75 mm in size, having a maximum to minimum dimension ration greater than 5:1 as tested in accordance with ASTM D 4791. The specification limit is no more than 10 percent by weight of the particles in the mix. Flat, elongated particles are limited because they can breakdown during processing of the aggregates through the HMA plant and/or during compaction, changing the in-place grading of the aggregates in the mix.

Clay Content (Sand Equivalency): This test (as described in Chapter 3) is used to estimate the relative portions of sand and clay like fines and dust in aggregates. A low sand equivalent value can be an indication that the aggregates source being used will produce an HMA mixture that has moisture susceptibility (stripping) problems.

Table 15.2 presents the FHWA's recommended requirements for the consensus properties. No national recommendation was made for the source properties. The criteria for these properties are determined by each user agency based on the aggregates in use in their area and experience with those aggregates.

Table 15.2 AASHTO-323, Superpave Aggregates Consensus Properties

ESALs (mil.)	Fractured Faces Coarse Aggregates, % min. (two crushed faces)		Uncompacted Voids Content of Fine Aggregates, % min.		Sand Equivalent, % min.	Flat & Elongated, % max.
	Depth from Surface		Depth from Surface			
	≤ 100 mm	≤ 100 mm	≤ 100 mm	> 100 mm		
< 0.3	55/–	–/–	–	–	40	–
0.3 to < 3	75/–	50/–	40	40	40	10
3 to < 10	85/(80)	60/–	45	40	45	10
10 to < 30	95/(90)	80/(75)	45	40	45	10
≥ 30	100/(100)	100/(100)	45	40	50	10

Aggregates Gradation

Federal Aviation Administration

The aggregates gradation requirements specified by the FAA is shown in Table 15.3.

Table 15.3 Federal Aviation Gradation Requirements

Aggregates Bituminous Pavements				
Sieve Size	**Percentage by Weight Passing Sieves**			
	1 ½" max	**1" max**	**¾ " max**	**½" max**
1 ½ in. (37.5 mm)	100	–	–	–
1 in. (25.0 mm)	86–98	100	–	–
¾ in. (19.0 mm)	68–93	76–98	100	–
½ in. (12.5 mm)	57–81	66–86	79–99	100
⅜ in. (9.5 mm)	49–69	57–77	68–88	79–99
No. 4 (4.75 mm)	34–54	40–60	48–68	58–78
No. 8 (2.36 mm)	22–42	26–46	33–53	39–59
No. 16 (1.18 mm)	13–33	17–37	20–40	26–46
No. 30 (0.600 mm)	8–24	11–27	14–30	19–35
No. 50 (0.300 mm)	6–18	7–19	9–21	12–24
No. 100 (0.150 mm)	4–12	6–16	6–16	7–17
No. 200 (0.075 mm)	3–6	3–6	3–6	3–6
Asphalt percent				
Stone or gravel	4.5–7.0	4.5–7.0	5.0–7.5	5.5–8.0
Slag	5.0–7.5	5.0–7.5	6.5–9.5	7.0–10.5

Superpave

Superpave uses the Bureau of Public Roads 0.45 power gradation chart for determining mix gradation. In application, aggregates percent passing is plotted against sieve size raised to the 0.45 power (see Figure 15.3). Following the 0.45 power curve approach, the maximum density gradation is defined by a straight line drawn from the origin to the maximum particle size on a 0.45 power graph. The maximum particle size is defined in the Superpave procedure as one size larger than the nominal maximum particle size. The nominal maximum particle size is defined as one sieve size larger than the first sieve having more than 10 percent retained.

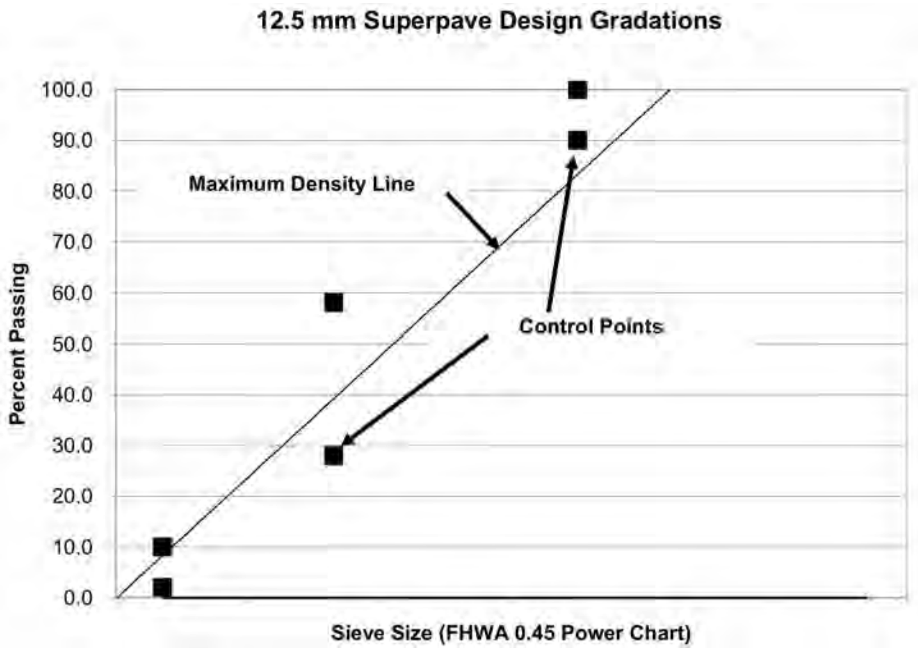

Figure 15.3 Superpave 0.45 Gradation Curve

Aggregates Grading: Recommended aggregates grading band and control points are given in Table 15.4. Control points for each nominal maximum aggregates size are just the sieve sizes for which an allowable range is given in the table for the percent passing. Only four standard sieve sizes are control sieves as shown in Table 15.4. In applying this grading approach, material engineers must carefully consider available ranges of aggregates stockpile sizes for effective plant processing. Also, providing a smooth transition of the gradation over consecutive sieve sizes helps to minimize segregation.

Table 15.4 Superpave Control Points

Sieve Size	Control Points									
	1 ½ inch (37.5 mm)		1 inch (25 mm)		3/4 inch (19 mm)		½ inch (12.5 mm)		3/8 inch (9.5 mm)	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
2 in (50 mm)	100.0	100.0	-	-						
1.5 in (37.5 mm)	90.0	100.0	100	100						
1 in (25 mm)		90.0	90	100	100	100				
¾ in (19 mm)				90	90	100	100	100		
½ in (12.5 mm)						90	90	100	100	100
3/8 in (9.5 mm)								90	90	100
No. 4 (4.75 mm)										90
No. 8 (2.36 mm)	15	41	19	45	23	49	28	58	32	67
No. 200 (0.075 mm)	0	6	1	7	2	8	2	10	2	10

The term used in Superpave to describe the aggregate gradation particle sizes is design aggregates structure. A design aggregates structure that lies between the control points meets the Superpave gradation requirements. Superpave defines six mixture gradations based on their nominal maximum aggregates size (see Table 15.5).

Table 15.5 Superpave Mixture Gradation

Superpave Designation, mm	Nominal Maximum Size, mm	Maximum Size, mm
37.5	37.5	50.0
25.0	25.0	37.5
19.0	19.0	25.0
12.5	12.5	19.0
9.5	9.5	12.5
4.75	4.75	9.5

Sampling: Laboratory mix design is a process that enables prequalification of material from existing aggregates stockpiles. The qualifying begins in the field when stockpile samples are collected. At that time, the general stockpile condition is evaluated including stockpile contamination, degree of segregation and aggregates moisture content. The mix design must be conducted on material that is representative of the stockpile. Sampling only should be performed by trained laboratory personnel to assure a representative aggregates gradation is obtained. Stockpile sampling techniques are described in Chapter 18.

Blending: Production of a consistent gradation to satisfy specification requirements requires blending two or more individually sized aggregates materials. Dense-graded mixtures with large top sizes may require blending as many as five materials. Several methods, which are discussed in Section 3.6 of Chapter 3, are available for use in determining appropriate proportions for each of the materials to be blended. The methods used include trial and error calculations, computer programs and graphical analysis.

Mix Design: The design of dense HMA mixtures involves a process of blending material from aggregates stockpiles to meet the specified gradation and estimating the optimum asphalt binder content to minimize occurrence of the following primary distress modes:

- Fatigue cracking
- Permanent deformation (rutting)
- Moisture sensitivity
- Thermal or shrinkage cracking

A laboratory mixture design is the best method of determining the optimum asphalt content. However, field conditions such as variations in stockpile gradations, asphalt plant mixing efficiency, temperature, aggregates moisture content, etc., alter mix characteristics. Often, minor adjustments to the job-mix formula are made in the field to obtain an optimum proportioning of aggregates and asphalt. For example, initial laboratory mix designs are based on gradations of a limited number of stockpile samples. Aggregates gradations obtained from stockpiles can change even though the aggregates are from the same source. Reasonable changes can be made in the blended gradation to compensate for the gradation available from the stockpile. A change such as this helps achieve the goal of producing an asphalt mixture with minimum gradation variation. When the adjustments do not produce the desired results, then a field laboratory redesign should be conducted.

Historically, the two most widely used mix design procedures were the Marshall (ASTM Test Method D 1559) and Hveem (ASTM D 1560) methods. Since 1990 the Superpave procedure has been the standard procedure for use by DOTs for highway construction. The Marshall Procedure is still used by the aviation community (FAA, DOD and the Corps of Engineers for Airfield Construction).

Comparison of Mix Design Methods: Generally, in conducting a mix design, samples are prepared using several asphalt content percentages to span the range from "too little" to "too much." Samples at each asphalt content are then compacted using a compactive effort specified by the mix design method used. The resulting specimens are evaluated for air voids, voids in the mineral aggregates and voids filled with asphalt. Subsequently, the specimens are loaded to determine their deformation behavior and/or strength. Evaluation criteria and their application for the Marshall and Hveem tests are presented in detail in the Asphalt Institute's manual, MS-2, *Mix Design Methods for Asphalt Concrete* and the Asphalt Institute's Manual *SP2 Superpave Mix Design*.

A direct comparison does not exist among the Marshall, Hveem and Superpave test procedures, because the tests measure different properties. But, all three mix design procedures are based on the use of volumetric analysis procedures.

Marshall Procedure

The concepts of the Marshall method of designing paving mixtures were formulated by Bruce Marshall, formerly a bituminous engineer with the Mississippi State Highway Department. The U.S. Corps of Engineers, through extensive research and correlation studies, improved and added certain features to Marshall's test procedure and ultimately developed mix design criteria. The Marshall test procedures have been standardized by the American Society for Testing and Materials (procedures given by ASTM Designation D-1559).

The Marshall method generally has been applicable to dense-graded HMA paving mixtures using performance graded (PG) asphalt binders and containing aggregates with a maximum size of one inch (25 mm) or less. It also has been adapted to the design of stone matrix asphalt (SMA) mixtures. The Marshall method is used for both laboratory design and quality control of hot mix asphalt pavements. For a detailed description of the steps and equipment needed to conduct a Marshall Mix Design, refer to the Asphalt Institute's MS-2 *Mix Design Methods* manual. The Asphalt Institute Mix Design Program SW-2 performs all the calculations needed to conduct a Marshall Mix Design. (It is recommended that mix designers refer to either AASHTO or ASTM requirements, or to the design agency's requirements so that those specific procedures can be followed.)

The Marshall method uses standard cylindrical test specimens of 2½ inches (64mm) in height by 4 inches (102 mm) in diameter. These are prepared using a specified procedure for heating, mixing and compacting the asphalt-aggregates mixtures. These specimens are compacted using a Marshall compaction hammer (Figure 15.4, see color section) and tested in a Marshall stability and flow device (Figure 15.5, see color section) The two principal features of the Marshall method of mix design are a density-voids analysis and stability-flow test of the compacted test specimens that were manufactured from asphalt and aggregates.

The stability of the test specimens is the maximum load resistance in pounds that the standard test specimen will develop at 140°F when tested as outlined here. The flow value is the total movement or strain, in units of 1⁄100 in (0.25 millimeter), occurring in the specimen between no load and maximum load during the stability test.

The Marshall mix design process consists of four basic steps:

1. Aggregates selection. This step consists of ensuring that the aggregates used in the mixture meets the agency's or the specifying engineer's requirements for the aggregates to be used in the mixture.
2. Asphalt binder selection.
3. Manufacturing of test specimens with a particular blend or gradation of aggregates. These test specimens are prepared for a range of different asphalt contents so that the test data curves show a well-defined "optimum" value. These samples are compacted using the Marshall compaction hammer (Figure 15.19). Depending on the requirements of the agency, generally either 50 blows or 75 blows are used.

4. Testing these samples to determine the volumetric properties and the Marshall stability and flow. This data is used to determine the optimum asphalt content for the mixture.

Whether the asphalt paving mix will be satisfactory from the design asphalt content selected is determined by applying certain limiting criteria to test data for the mix at its design asphalt content. An engineer designing an HMA mixture for an agency should check that agency's specific requirements. If all the criteria are met, then this is the design asphalt content. If any of the design criteria are not met, then some adjustment is necessary or the mix may need to be redesigned.

The mix design selected for use in a pavement is usually the one that most economically meets all the established criteria. However, the mix should not be designed to optimize one particular property. For example, mixes with abnormally high values of stability often are less desirable because pavements with such mixes tend to be less durable and might crack prematurely under heavy volumes of traffic. Any variations in design criteria should be allowed only under unusual conditions, unless the service behavior of specific aggregates mixture indicates that such a variant paving mix is satisfactory.

Superpave Procedure

The Superpave mix design procedure is the result of an extensive research study that was conducted in the late 1980s and implemented by the various state DOTs in the 1990s. The primary difference between the Marshall Mix Design Procedure and the Superpave Mix Design Procedure is the compactor used to manufacture the samples. Both procedures use volumetric analysis procedures to analyze the mix.

The following presents a brief outline of the Superpave mix design procedure. The major difference between the Superpave design procedure and the Marshall procedure is the compaction equipment. The Superpave design procedure uses a gyratory compactor to compact the specimens.

- Select asphalt and aggregates materials that meet the design criteria.
- Develop several aggregates trial blends that will meet the Superpave gradation requirements.
- Blend the asphalt binder with the aggregates trial blends and short-term oven aging of the mix.
- Compact the specimens.
- Analyze the volumetric properties of the mixture (use the same procedures as the Marshall design procedure).
- Select the best aggregate blend as the design aggregates structure based on the desired performance criteria for the mixture.

A detailed discussion is provided in the Asphalt Institute's *Superpave* manual (SP-2).

The Superpave mix design procedure uses the Superpave Gyratory Compactor (SGC) (Figure 15.6, see color section) to compact the specimens. A gyratory compactor was used to try to manufacture an HMA mixture in the laboratory that would have similar characteristics as an HMA mixture would have on the roadway. The SGC is a mechanical device comprising the following components:

- Reaction frame, rotating base and motor
- Loading system, loading ram and pressure gauge
- Height measuring and recordation system
- Mold and base plate
- Specimen extruding device

A loading mechanism presses against the reaction frame and applies a load to the loading ram to produce a 600-kPa compaction pressure on the specimen. A pressure gauge measures the ram loading to maintain constant pressure during compaction. The SGC mold has an inside diameter of 150 mm and a base plate in the bottom of the mold provides confinement during compaction. The SGC gyrates at a constant rate of 30 gyrations per minute with the mold positioned at an external compaction angle of 1.25 degrees. Specimen height measurement is an important function of the SGC. Using the mass of material placed in the mold, the diameter of the mold and the specimen height, an estimate of specimen density can be made at any time throughout the compaction process. Specimen density is computed by dividing the mass by the volume of the specimen. The height is measured by recording the position of the ram throughout the test. Using these measurements, a specimen's compaction characteristic is developed (see Figure 15.7).

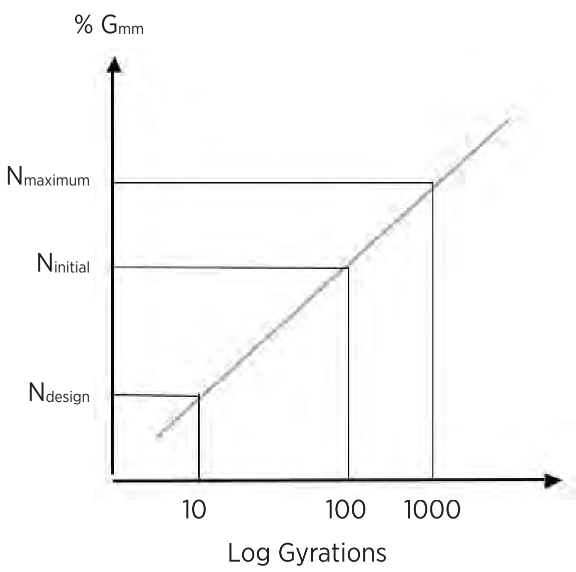

Figure 15.7 Mixture Compaction Characteristics from the SGC

Figure 15.7 illustrates how the density of the asphalt mixture increases with increasing gyrations. As with other mix design procedures, asphalt mixtures are designed at a specific level of compaction effort. In the Superpave mix design system, this is a function of the design number of gyrations (N_{des}). N_{des} is used to vary the compactive effort of the design mixture, and it is a function of the traffic level. Traffic is represented by the design Equivalent Single Axle Loads (ESALs). The range of values for N_{des} is shown in Table 15.6.

Table 15.6 Superpave Gyratory Compactive Effort

Design ESALs* (million)	Compaction Parameters			Typical Roadway Applications
	$N_{initial}$	N_{design}	$N_{maximum}$	
< 0.3	6	50	75	Applications include roadways with very light traffic volumes, such as local roads, county roads and city streets where truck traffic is prohibited or at a very minimal level. Traffic on these roadways would be considered local in nature, not regional, intrastate or interstate. Special purpose roadways serving recreational sites or areas may also be applicable to this level.
0.3 to 3	7	75	115	Applications include collector roads or access streets. Medium-trafficked city streets and the majority of country roadways may be applicable to this level.
3 to < 30	8	100	160	Applications include many two-lane, multilane, divided and partially or completely controlled access highways. Among these are medium to heavily trafficked city streets, many state routes, U.S. highways and some rural intersections.
> 30	9	125	205	Applications include the vast majority of the U.S. Interstate System, both rural and urban in nature. Special applications such as truck-weighing stations or truck-climbing lanes on two-lane roadways may also be applicable to this level.

** The number of ESALs expected over a 20-year life of the roadway.*

Strength Testing

The performance of asphalt concrete mixtures when subjected to a moving wheel load is difficult to predict from conventional laboratory test results. Significant interest has therefore developed in the use of laboratory *wheel tracking test devices* (WTD) to predict performance. In general, depending on the equipment capability, the WTD involves moving a loaded wheel back and forth over the surface of a compacted asphalt concrete mixture. Rutting and/or stripping potential of the asphalt concrete mix can be determined after a relatively few number of wheel repetitions. Consequently, the WTD is used to verify mixture designs and as a screening device for prototype scale accelerated pavement testing studies. The WTDs do not provide fundamental engineering properties that can be used in calculations of stresses and strains in an HMA pavement. Rather they have shown through field performance to be indicative of performance. The two most common devices are the Hamburg Wheel Tracking Device (HWTD) and the Asphalt Pavement Analyzer.

Hamburg Wheel-Tracking Device: This machine was developed by the Germans in the 1970s. The test procedure is AASHTO T-324. The HWTD measures the combined effects of rutting and moisture on an HMA mixture. A steel wheel rolls across the surface of the HMA core, which is immersed in hot water. The steel wheel moves through a crank connected to a flywheel. The steel wheel has a diameter of 8 inches (204 mm) and is 1.85 inches (47 mm) wide with a 154-pound load applied. The testing is done with the samples in a hot water bath at 50°C. The test is run for 10,000 cycles (20,000 passes) or until a deformation of 0.787 inch (20 mm) is reached. The machine is shown in Figure 15.9 (see color section). The HWTD can be used to evaluate the resistance of an HMA mix to rutting and moisture susceptibility (stripping).

Asphalt Pavement Analyzer: The Asphalt Pavement Analyzer (APA) is a modification of the Georgia Loaded Wheel Tester (GLWT), which was developed in a cooperative study of the Georgia Department of Transportation and the Georgia Institute of Technology in 1985. It has been used primarily to evaluate the rutting resistance of an HMA mixture. Studies have been conducted to evaluate the use of the equipment for evaluating fatigue and moisture resistance of HMA mixtures. The APA is shown in Figures 15.10 (see color section). A loaded wheel is placed on a pressurized hose, which sits on the test specimens, and then tracked back and forth to induce rutting. Generally, the specimens are tested to 8,000 cycles. Samples can be tested dry or while submerged in water. The test specimens for the APA can be either beam or cylindrical specimens. The beam samples generally are compacted using the Asphalt Vibratory Compactor. The cylindrical specimens are made with the Superpave Gyratory Compactor. The beams are compacted to 7 percent air voids, and the cylindrical specimens are compacted to both 4 and 7 percent air voids. Cores from an in-service roadway also can be tested. The samples are tested at or near the maximum pavement temperatures (generally defined as the high temperature grade for the asphalt binder to be used in region where the HMA pavement is being built). The APA can be used to evaluate the rutting resistance of an HMA mixture.

Stripping: For both the Marshall and Superpave mix design procedures moisture stability or stripping is evaluated. Stripping is the loss of adhesion between asphalt and aggregate due to moisture sensitivity. Stripping of HMA mixtures will result in surface raveling, mixture instability and the loss of asphalt coating. The presence of moisture may initially cause lack of bond between the asphalt and aggregates. Moisture can later lead to a weakening or a loss of bond. Major material and construction factors contributing to potential stripping of asphalt concrete mixtures are:

- Use of siliceous and other hydrophilic aggregates susceptible to stripping (refer to Chapter 3)
- Poor mix design
- Inappropriate construction practices
- Inadequate quality control
- Low pavement densities
- Inadequate pavement drainage

One of the above factors, acting independently, might not be detrimental, but when combined with other factors, stripping problems can occur. Stripping in asphalt concrete pavements is one of the significant causes of deterioration in some areas. Figure 15.7 provides a guide to evaluating stripping potential. In applications involving heavy volumes of high tire-pressure traffic, dense-graded mixtures with a high percentage of crushed aggregates and limited natural sand produce a stable asphalt concrete mixture. In such mixtures, the required density should be high and the asphalt content should be adequate to provide durability without creating instability. A high density is achieved when aggregates particles are crowded closely together leaving only enough void space to accommodate the specified asphalt and 3 to 5 percent of air voids within the mixture. Mix designs for pavements or other surfaces with limited or no traffic can be adjusted to use less crushed material and higher asphalt contents.

Mechanistic-Empirical Pavement Design Guide: Properties of the Mixture

The dynamic of the AC sublayers is the single most important engineering property of the dense graded HMA layer in MEPDG. This is because in order to compute pavement responses to load, which are used in computing fatigue and rutting damage within all pavement layers, reliable layer moduli are required. Furthermore, in the constitutive relationships required for layered elastic analysis, upon which the MEPDG structural analysis is based, layer moduli along with layer Possion's ratios are required.

Since the modulus of the HMA layer and/or sublayers is time and temperature dependent, the dynamic modulus was selected to represent and model HMA layers. The dynamic modulus is measured by imparting a sinusoidal stress pulse to a cylindrical HMA sample. The test is conducted over a range of combinations of frequency of the sinusoidal pulse and temperature in order to cover the range of frequencies and temperatures representative of the pavement environment. The procedure for dynamic modulus testing under compressive loading is presented in a provisional standard, AASHTO TP 62. In this procedure, the peak stress level maintains a total measured strain of between 50 and 150 microstrain, which has been determined experimentally to be within the linear viscoelastic range of HMA mixtures used for pavements. Although a creep effect is induced in the cyclic loading, it is ignored and only the dynamic modulus is measured as the ratio of the amplitude of the stress function to the amplitude of the dynamic strain function.

Data obtained from the dynamic moduli tests over a range of frequencies and for various temperatures are used to construct a master curve for the HMA mixture. MEPDG recommends the use of a sigmoidal function to describe the master curve:

$$\log|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma \log t_r}} \qquad [15\text{-}1]$$

Where tr is reduced time (where time may be considered to be the reciprocal of frequency), which is defined as at the reference temperature, $|E^*|$ is the minimum value of , $\delta + \alpha$ is the maximum value of $|E^*|$, and β and γ are parameters which describe the shape of the sigmoidal function. These parameters are expressed within MEPDG as functions of mixture volumetrics and gradation. In Level 1 of MEPDG the master curve is the result of *dynamic modulus testing* at temperatures of 10, 40, 70, 100 and 1300F (-12, 4, 21, 38 and 540C) and for each temperature at frequencies of 0.1 Hz, 1 Hz, 10 Hz and 25 Hz.

Values of δ and α in equation [15-1] can be calculated based on certain properties of the aggregate and mixture as follows:

$$\delta = -1.249937 + 0.02932\,\rho_{200} - 0.001767\left(\rho_{200}\right)^2 - 0.002841\,\rho_4 - 0.05809\,V_a - 0.802208 \left[\frac{V_{b_{eff}}}{V_{b_{eff}} + V_a}\right] \qquad [15\text{-}2]$$

$$\alpha = 3.871977 - 0.0021\,\rho_4 + 0.003958\,\rho_{3/8} - 0.0000\,\rho_{3/8}^2 + 0.005470\,\rho_{3/4} \qquad [15\text{-}3]$$

where

V_a = Air void content, %.
$V_{b\ eff}$ = Effective bitumen content, % by volume.
$\rho_{3/4}$ = Cumulative % retained on the ¾ inch sieve.
$\rho_{3/8}$ = Cumulative % retained on the ⅜ inch sieve.
ρ_4 = Cumulative % retained on number 4 sieve.
ρ_{200} = Cumulative % passing the number 200 sieve.

In Levels 2 and 3 of MEPDG the dynamic modulus can be predicted over a range of temperatures, rates of loading and aging conditions from information that is readily available from material specifications or volumetric design of the mixture:

$$\log E^* = -1.249937 + 0.02932\,\rho_{200} - 0.001767\left(\rho_{200}\right)^2 - 0.002841\,\rho_4 - 0.05809\,V_a - 802208\left[\frac{V_{b_{eff}}}{V_{b_{eff}} + V_a}\right] + \frac{3.871977 - 0.0021\,\rho_4 + 0.003958\,\rho_{3/8} + 0.005470\,\rho_{3/4}}{1 + e^{\left(-0.603313 - 0.31335\log(f) - 0.393532\log(\eta)\right)}} \qquad [15\text{-}4]$$

where

n = Viscosity, x106 Poises
f = Loading frequency, Hz.

15.5 Open-Graded Friction Course

An open-graded friction course (OGFC) is typically a thin surface layer ¾- to 1-inch thick having a coarse macrotexture and large amount of internal voids. An open-graded friction course is also called a porous friction course (PFC) or plant mix seal (PMS). In the United States, the OGFC was developed as a pavement surface treatment to give high friction and reduce hydroplaning potential. Hydroplaning is the condition where the tires of a fast moving car, truck or aircraft hydroplane on a pressurized film of water. Other benefits of using an OGFC are:

- A minimum of material is used to provide high skid resistance
- The riding quality of existing, structurally sound pavements is extended
- Minor surface irregularities are corrected
- Quieter riding surfaces are provided
- Tire splash and spray are reduced
- Visibility of paint stripes and other pavement markings is improved in wet weather
- Night visibility is improved during wet weather due to less glare from the pavement surface
- Traffic delays caused by construction are minimized

The primary benefit of an OGFC is to reduce hydroplaning potential through pressure relief in the water film between a vehicle's tires and the pavement surface. High internal voids and the coarse surface macro texture of an OGFC contribute significantly to pressure relief. The functions performed by an open-graded friction course can be grouped according to the following two characteristics. The high internal voids provide:

- Internal pressure relief channels
- Flow channels for internal drainage of surface water
- Temporary storage of a small amount of surface water
- Coarse surface macro texture that provides:
- Pressure relief channels on the surface
- Flow channels for surface water
- In general, tire-pavement contact above surface water film

Aggregates Requirements

Aggregates Properties: The coarse aggregates used in an OGFC should have an L.A. Abrasion value of less than 30 percent. Soft aggregates should be avoided due to the potential for breakdown during mix production and compaction in the field. The aggregates should have 100 percent fractured faces to provide high internal friction. If crushed gravel is used, it should have at least 95 percent of the particles with two fractured faces and 100 percent with one fractured face. The fractured faces on gravels should be produced by mechanical fracturing of the rock. The percentage of flat and elongated particles should not exceed five to 20 percent corresponding to ratios of 5:1 and 3:1. The fine aggregate used in the mixture should have a fine aggregates angularity of at least 45 percent or higher.

Gradation: The aggregate gradation limits for OGFC according to ASTM D3515 is shown in Table 15.7.

Table 15.7 ASTM D 3615 Gradation for Open-Graded Friction Courses*

Sieve Size	Type I – ¾ inch (19 mm)	Type II – ½ inch (12.5 mm)
	Percent Passing	
¾ in (19 mm)	100	100
½ in (12.5 mm)	100	90 – 100
3/8 in (9.5 mm)	90 -100	60 – 100
No. 4 (4.75 mm)	30 – 50	15 – 40
No. 8 (2.36 mm)	5 – 15	4 - 12
No. 200 (0.075 mm)	2 - 5	2 - 5
Asphalt - % of total mixture	5 – 8 ½	4 ½ - 8

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Mix Design

Mix design for an OGFC is based on providing an adequate coating to hold the aggregate in place. In addition, excess asphalt is desirable so that some asphalt drains to the interface with the underlying surface. The asphalt which drains to the interface bonds the OGFC to the supporting surface. However, use of too much asphalt reduces the permeability of the OGFC. Also, the asphalt quickly flushes to the surface so that the desirable rough macro texture is lost.

The Asphalt Institute's Manual MS-4 *The Asphalt Handbook* provides a detailed description of the design procedure for an OGFC.

15.6 Open-Graded Base Mixes

An open-graded base mix is placed as a drainage layer under either an HMA or PCC pavement. The coarse aggregate should be crushed and cubical to provide good interlock. The asphalt binder content for this type of mix will range from 1.5 to 2.5 percent. These mixes are very permeable and will provide rapid drainage for subsurface water. They need to be day lighted or connected to a subdrainage system to allow the moisture to drain out. Figure 15.8 shows a typical gradation for a permeable drainage layer.

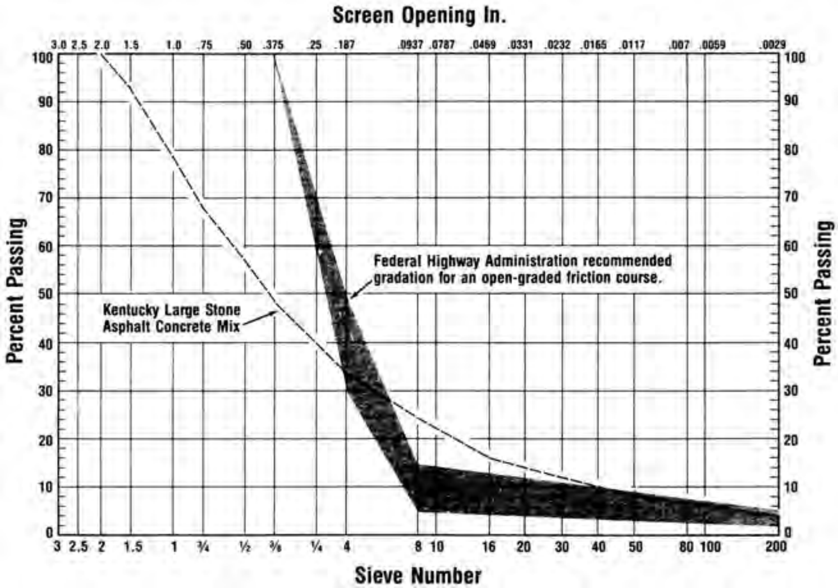

Figure 15.8 Typical Gradation for an Open Graded Base Layer

15.7 Stone Matrix Asphalt

Stone Matrix Asphalt (SMA) mixtures have been used in the United States since 1991. These mixtures have performed well in Europe for many years and experience in the United States is similar. SMA is a rut-resistant, gap-graded HMA. The mix relies on stone-on-stone contact to provide its internal strength. The mix uses a high asphalt binder content of 6 to 7 percent or more. This high binder content provides improved durability. In most situations, the asphalt binder is generally a polymer-modified asphalt. Mineral filler and either mineral or cellulose fibers are added to form a stiff mortar and prevent draindown of the asphalt cement. The in-place air voids are kept low—to less than 6 percent to ensure that the mix is impermeable to water. SMA is routinely used in many states as the surface of choice for high-volume roadways and intersections. Refer to the AASHTO Provisional Procedure PP-41-02 (2004) *Designing Stone Matrix Asphalt (SMA)*.

Mix Design

The mix design process consists of the following five steps:
1. Select proper materials (aggregates, asphalt binder, mineral filler and fibers).
2. Determine the aggregates gradation that yields stone-on-stone contact.
3. Ensure that the selected gradation provides the minimum required VMA.
4. Choose an asphalt binder content that provides the desired air voids.
5. Evaluate the mix for moisture susceptibility.

Aggregates Requirements

SMA mixtures require the use of high-quality aggregates. AASHTO specifications require that 100 percent of the coarse aggregates have at least one crushed face and at least 90 percent must have two or more crushed faces. The strength of a SMA mixture is achieved through stone-on-stone contact. Therefore, most agencies have placed more stringent requirements on aggregates used in SMA. AASHTO requires a maximum L.A. Abrasion loss of 30 percent. But some states—because of a lack high-quality aggregates—have built successfully performing projects with a less stringent requirement. Table 15.8 presents the aggregates requirements for SMA mixes and Table 15.9 presents the typical gradations used for SMA mixes.

Table 15.8 AASHTO MP-8, SMA Aggregates Quality Requirements

Coarse Aggregates		
Los Angeles Abrasion, %		30 max.
Flat & Elongated, %	3:1	20 max.
	5:1	5 max.
Absorption, %		2.0 max.
Soundness (5 cycles), %	Sodium Sulfate	15 max.
	Magnesium Sulfate	20 max.
Crushed Content	One Face	100 min.
	Two Faces	90 min.
Fine Aggregates		
Soundness (5 cycles), %	Sodium Sulfate	15 max.
	Magnesium Sulfate	20 max.
Liquid Limit, %		25 max.
Plasticity Index		Non-plastic

Table 15.9 Typical Gradations for SMA Mixes (Percent Passing by Volume)

Sieve Size	Mixture Designation		
	¾ In (19 mm)	½ in (12.5 mm)	3/8 in (9.5 mm)
1 in (12.5 mm)	100		
¾ in (19.0 mm)	90–100	100	
½ in (12.5 mm)	50–88	90–100	100
⅜ in (9.5 mm)	25–60	50–80	70–95
No. 4 (4.75 mm)	20–28	20–35	30–50
No. 8 (2.36 mm)	16–24	16–24	20–30
No. 16 (1.18 mm)	–	–	21 max.
No. 30 (0.60 mm)	–	–	18 max.
No. 50 (0.30 mm)	–	–	15 max.
No. 200 (0.75 mm)	8–11	8–11	8–12

Construction and effect of aggregates properties on construction: The use of cubical, textured aggregates will require greater attention to providing sufficient compactive effort to obtain the required density than an HMA mixture with a smooth-textured aggregate. The use of a smooth aggregates can result in a mixture that is easy to compact but may continue to compact under traffic resulting in rutting due to low voids and plastic flow of the mixture.

15.8 Sampling and Testing Requirements

The overwhelming goal is to obtain samples that are representative of the products being evaluated. Since test results are used to adjust hot plants, it would be counterproductive to overall quality to obtain a sample from a particularly "bad" or a particularly "good" portion of the work. Consider as an example an HMA plant quality-control sample taken from a non-representative portion of the HMA mixture with an unusually low binder content. The proper response from the plant operator to a low asphalt content test result would likely be to increase the amount of asphalt binder being incorporated into the mix. After such an adjustment, the plant operator would inadvertently have the asphalt plant set too high for asphalt cement content.

Representative samples of the average production are critical for the effective use of quality-control and acceptance samples. Inspection is more appropriate for identifying non-uniform portions of the work. Once inspection has identified a portion of the work that is non-uniform (different from the rest of the work), or for which defective materials are suspected, additional samples representing that specific element of the work should be taken. Test results from such samples should never be used as part of the lot averages, and certainly not for lot acceptance. They only represent the specific problem areas identified by inspection.

As an example, consider an asphalt pavement that contains a 50-foot (15.2 meters) length of roadway that is littered with manholes and valve covers that do not allow the regular compaction equipment into that isolated area. By visually observing the entire pavement, an inspector or technician would be able to recognize that the isolated area will not have density values that are representative of the pavement compaction for that day's placement. Density tests taken there would represent that area only.

Regardless of the methods being employed, good samples will be obtained if a common sense approach is combined with proper sampling technique. Visual observations of the entire element to be sampled can be valuable in selecting sample locations, number of sample collection points and in verifying that representative samples can be retrieved.

It also is important to get a sufficient quantity of material when sampling. The sample size is important not only to obtain enough material to complete the tests but also to achieve a representative sample. As an exaggerated example, consider a graded gravel material that contains

15 percent of rock that is retained on the ¾-inch (19 mm) screen and passes the 1-inch (25 mm) screen. Each of these + ¾-inch (19 mm) rocks weigh about 250 grams. Say a sample size of only 500 grams is obtained. If the sample taken happens to contain one large rock, then the gradation test will yield 50 percent retained on the ¾-inch (19 mm) sieve. If the 500-gram sample scoop doesn't happen to capture a large rock, then the gradation test would yield 0 percent of that size. In reality, the gradation is somewhere between 0 and 50 percent. As the sample size increases, the test result no longer is impacted by the size of the sample—it is only impacted by the true gradation of the materials being tested. This is the point that establishes minimum sample sizes. Typical minimum sample sizes for aggregates and for HMA are presented in Table 15.10.

Table 15.10 Minimum Sample Size for Aggregates

Nominal Maximum Aggregates Size		Aggregates		HMA	
		Minimum Sample Weight		Minimum Sample Weight	
English	Metric	English	Metric	English	Metric
No. 8	2.36 mm	10 lb	5 kg	4 lb	2 kg
No. 4	4.75 mm	10 lb	5 kg	4 lb	2 kg
⅜ in	9.5 mm	10 lb	5 kg	8 lb	4 kg
½ in	12.5 mm	20 lb	10 kg	12 lb	5 kg
¾ in	19.0 mm	30 lb	20 kg	16 lb	7 kg
1 in	25.0 mm	50 lb	30 kg	20 lb	9 kg
1½ in	37.5 mm	70 lb	50 kg	25 lb	11 kg

15.9 Surface Treatments

Chip Seals

A chip seal is the application of a bituminous binder immediately followed by the application of an aggregate. The aggregates are then rolled to embed it into the binder. Multiple layers may be placed and various binder and aggregates types can be used to address specific distress modes or traffic situations. There are many different types of chip seals in use by agencies. Types of chip seal treatments include:

- **Single Chip Seal:** A single chip seal is an application of binder followed by an aggregates. This is used as a pavement preservation treatment and provides a new skid resistant wearing surface, arrests raveling and seals minor cracks

- **Multiple Chip Seal:** A multiple chip seal (or armor coat) is a built-up seal coat consisting of multiple applications of binder and aggregates. As an example, a double chip seal consists of a spray application of binder, spreading a layer of aggregates, rolling the aggregates for embedment, applying an additional application of binder, spreading another layer of aggregates (approximately half the average least dimension of the base coat aggregates) and rolling once more. Sweeping should be done between applications. This process may be repeated, as necessary, to build up a pavement's edges. Multiple chip seals are used where a harder wearing and longer lasting surface treatment is needed.

The main advantages associated with chip seals include (Caltrans):

- **Improved Skid Resistance:** Chip seals provide good skid resistance.

- **Cost Effective Treatments:** Chip seals are typically cost effective when properly placed on the right type of pavement.

- **Good Durability:** Chip seals wear well and can have long service lives.

- **Ease of Construction:** Chip seals are typically constructed rapidly and cause less disruption to the traveling public than do other treatments that take longer.

Aggregate Characteristics

The aggregate used for a chip seal will have a significant affect on the overall performance of the completed chip seal. There are four properties of importance to the chip seal:

- **Clean.** Good short-term, as well as long-term, bond of asphalt to the aggregates are important. Dusty aggregates as well as excess moisture inhibits asphalt-aggregates bond. The aggregates used for a chip seal should be clean and free from coatings of dust or other foreign material with preferably less than 1.5 percent passing the 0.075 mm (No. 200) sieve (based on a washed gradation). Precoating the aggregates is one technique of enhancing aggregates retention on the roadway. In precoating prior to placement, the aggregates are dried, cooled and mixed with about 1 percent of an emulsified or cutback asphalt which is analogous to an application of tack coat

- **Hardness.** An L.A. abrasion rating of 25 maximum is sometimes stipulated for heavier traffic (more than 1,000 vehicles per day) while an L.A. rating up to 40 may be accepted for light traffic (under 500 vehicles per day). However, locally available aggregates tend to be employed as cover materials regardless of the L.A. abrasion value. The advantage of an L.A. abrasion rating of 26 or less is that this usually ensures a tough aggregates with much less tendency to break up or wear away under the influence of traffic and climate.

- **Gradation.** ASTM D 1139 provides the gradation requirements for cover aggregates for single and multiple chip seals (see Table 15.12). The use of large maximum size aggregates for a chip seal creates substantial tire noise which can be objectionable to the user. Also, large aggregates, if loosened, may cause significant windshield breakage as traffic is applied. As a result, many agencies have a policy of selecting a maximum aggregates size so that the large aggregates bounces off of windshields rather than breaks them. Windshield breakage is a particular problem on high-speed roads carrying heavy traffic and some agencies have limited the use of surface treatments to low-volume roads.

- **Shape.** Surface treatment aggregate should be crushed. Uncrushed, rounded aggregates particles are not stable (they do not provide aggregates interlock) and often exhibit inadequate skid resistance.

Table 15.11 ASTM D1139* Recommendations for Aggregates Sizes, Quantities of Aggregates and Quantities of Bitumen for Surface Treatments

Surface Treatment		Aggregates			Bituminous Material[2]
Type		Size No.[3]	Nominal Size (Square Openings)	Typical Rate of Application (ft^3/yd^2)[1]	Typical Application Rate Application (gal/yd^2)
Single	Initial	5	1 in to ½ in	0.50	0.42
		6	¾ in to 3/8 in	0.36	0.37
		7	½ in to No. 4	0.23	0.23
		8	3/8 to No. 8	0.17	0.19
		9	No. 4 to No. 16	0.11	0.13
Double	Initial	5	1 in to ½ in	0.50	0.42
	Second	7	½ in to No. 4	0.25	0.26
Double	Initial	6	¾ in to 3/8 in	0.36	0.37
	Second	8	3/8 in to No. 8	0.18	0.20
Triple	Initial	5	1 in to ½ in	0.50	0.42
	Second	7	½ in to No. 4	0.25	0.26
	Third	9	No. 4 to No. 16	0.13	0.14
Triple	Initial	6	¾ in to 3/8 in	0.36	0.37
	Second	8	3/8 to No. 8	0.18	0.20
	Third	9	No. 4 to No. 16	0.13	0.14

1. *The values are typical design or target values and not necessarily obtainable to the precision indicated.*
2. *Experience has shown that these quantities should be increase slightly (5 to 10%) when the bituminous material to be used was manufactured for application with little or no heating*
3. *According to Specification D 448*

Design

Many agencies use a recipe approach for surface treatment mix design in which an acceptable range of asphalt content and rate of a given aggregates size is specified. Actual amounts of both asphalt and aggregates used are based on experience, including some adjustments for existing site conditions. A dry, open surface requires a higher asphalt application rate than a dense, flushed surface. The Asphalt Institute's manual MS-4, *The Asphalt Handbook* provides a detailed explanation of the design of chip seals. The selection of an asphalt application rate, aggregates size, spacing and embedment are all considered in this mix design procedure.

Asphalt Binder

Generally a rapid setting emulsified asphalt (CRS-1, RS-1) is used for chip seal construction. These emulsions may be polymer modified to provide a binder with improved adhesion. In some states a paving grade asphalt is used. It is recommended to check with the local Department of Transportation maintenance section about which binder works best for the local climate. In chip seal design, the residual binder application rate is the most important factor affecting seal performance. Enough binder must be present to hold the aggregates in place, but not so much that the binder fills or is forced by traffic action to cover the aggregates. The proper amount of binder ensures that the desired surface texture is maintained. Chip seal design is not like hot mix asphalt design, in that film thickness is not as applicable a concept. Binder application rates are determined based on the average least dimension of the aggregates, as well as other aggregates properties such as shape, density, absorption and grading. The optimum binder content also depends on how much binder flows into existing voids in the pavement, and how much binder already is present at or near the pavement surface.

Construction

Distributors for spraying the asphalt binder and aggregates spreaders used in the construction of surface treatments should be in good condition and calibrated so that both components are applied uniformly at the correct rate. Precautions should be taken to ensure that incompatible asphalt binders such as anionic and cationic emulsions are not blended in distributors that are contaminated with the opposite type of asphalt. Emulsions are particularly sensitive to incompatibility which can cause a separation of the water and asphalt phases. Moisture left in a distributor tank or present on the aggregates can cause foaming problems when in contact with hot asphalt. Proper distribution of asphalt from a distributor depends upon maintaining even pressure throughout the system. Nozzles should be in good condition and clean for even spraying. The nozzles on the spray bar should be angled so that the spray from one nozzle does not interfere with that from another. Also the spray bar height should be adjusted so that overlap of the spray fans is correct for the amount of asphalt applied.

To ensure that the asphalt does not cool before the aggregates are embedded, aggregates application should occur immediately after asphalt application. Application of the proper amount of asphalt and aggregates ensures good performance as well as being economical. After aggregates spreading, the surface should be rolled with a pneumatic roller. The use of a pneumatic roller results in contact with all of the aggregates on an uneven surface. A steel-wheeled roller should not be used since it would bridge across low spots. The surface should not be rolled too much. Excess rolling loosens the aggregates as the asphalt cools and traffic subsequently whips the aggregates off the surface.

Precautions

Controlling the speed of traffic allowed on a surface treatment just after construction also is important. High-speed traffic causes aggregate in a freshly placed surface treatment to be broken loose. This loose aggregates can be thrown into the air and break windshields. Loose or excess aggregates should be removed with a rotary broom after the asphalt has set completely. Environmental conditions are important for the successful application of surface treatments. Cool, damp or shady conditions or a combination of the three during construction can lead to poor performance of a surface treatment. Experience has shown that surface treatments placed before a certain date in the spring or after a certain date in the fall perform poorly, and therefore, seasonal limits for given geographic areas usually are placed on surface treatment construction.

Slurry Seals

Slurry seals are a mixture of asphalt emulsion, well-graded fine aggregates, water and mineral filler. These components are mixed so that the product is homogeneous and fluid. The mineral filler is often a hydrated lime or cement which combines with the water and asphalt to form a high specific gravity liquid medium that supports the larger mineral aggregates. This liquid is somewhat analogous to the drilling mud used to remove rock cuttings during subsurface explorations. A squeegee, which is an integral part of the construction equipment, is used to place a slurry seal onto the pavement surface. As a result, the thickness of the slurry seal is dictated by the maximum size of aggregate. In general, slurry seals can fill small cracks in the pavement surface, reduce raveling, protect the existing pavement, as well as provide a skid-resistant surface. The surface on which the slurry seal is placed should be structurally sound. Cracks larger than hair line in size reflect through a thin slurry seal and weak areas quickly deteriorate under traffic.

Asphalt Binder

The asphalt emulsion used in the slurry seal may be a SS-1, CSS-1, SS-1h, QS-1h, CSS-1h or CQS-1h. The cement mixing test is waived for CQS-1h and QS-1h emulsions. The correct emulsion for any given slurry seal aggregates should be verified by a mix design.

Aggregates

The aggregates used in slurry seals should be well graded. In effect the slurry gradations are scaled down versions of dense hot mix gradations. A dense gradation has a distribution of aggregates particles that key with one another to provide a tight, dense, wear resistant surfacing. Slurry seal gradations as recommended by the International Slurry Seal Association (ISSA) are shown in Table 15.12. A slurry seal aggregates should be clean and predominately crushed. In general, increasing the amount of natural sand used results in increasing wear and poor performance of slurry seals. Since the aggregate is subjected to intense loadings at the surface of the pavement, the toughness and durability of the aggregates should be equal to that of a high-quality, hot asphalt mixture.

An individual aggregate or a blend of aggregates to be used in a slurry mix should meet these limits:

- Sand equivalent value, ASTM D 2419 (AASHTO T 176) = 45 minimum;
- L.A. abrasion loss, ASTM C 131 (AASHTO T 96) Grading C or D = 35 maximum; and,
- The amount of smooth-textured sand of less than 1.25 percent water absorption is limited to not more than 50 percent of the total combined aggregates.

The three generally accepted gradations used for slurry mixtures are shown in Table 15.12.

Type I is used for maximum crack penetration. Also, it makes an excellent pretreatment for hot-mix overlay or chip seal. It usually is used in low-density traffic areas such as light aircraft airfields, parking areas or shoulders where the primary objective is sealing.

Type II is the most widely used gradation. It is used to seal; correct severe raveling, oxidation and loss of matrix; and improve skid resistance. It is used for moderate traffic, depending upon the quality of aggregates available and the design.

Type III is used to correct surface conditions, as the first course in multi-course applications for heavier traffic and to provide skid resistance.

Table 15.12 Slurry Seal Aggregates Gradings (ISSA)

Type of Slurry	I	II	III
General Usage	Crack filling and fine seal	General seal, medium textured surfaces	1st and/or 2nd application, two-course slurry, highly textured surfaces
Sieve Size	**Percent Passing**		
⅜ in. (9.5 mm)	100	100	100
No. 4 (4.75 mm)	100	90-100	70-90
No. 8 (2.36 mm)	90-100	65-90	45-70
No. 16 (1.18 mm)	65-90	45-70	28-50
No. 30 (600 μm)	40-65	30-50	19-34
No. 50 (300 μm)	25-42	18-30	12-25
No. 100 (150 μm)	15-30	10-21	7-18
No. 200 (75 μm)	10-20	5-15	5-15
Residual Asphalt Content, % Weight of dry aggregate	10-16	7.5-13.5	6.5-12
Application Rate, lb/yd^2 (kg/m^2), based on mass (weight) of dry aggregate	6-10 (3-5.5)	10-15 (5.4-20)	18-30 (8.2 - 30)

** Recommended by International Slurry Surfacing Association*

A slurry seal aggregates should be clean and predominately crushed. In general, increasing the amount of natural sand used results in increasing wear and poor performance of slurry seals. Since the aggregates are subjected to intense loadings at the surface of the pavement, the toughness and durability of the aggregates should be equal to that of a high-quality, hot asphalt mixture.

Slurry Seal Tests

Residual Asphalt Content: ISSA describes tests used to evaluate slurry seal specimens. However, only a general range of residual asphalt content is recommended for each of the three gradations. Residual asphalt content is the amount of asphalt in the slurry exclusive of the water in the original emulsion or water added in preparation of the slurry. A surface area method has been proposed for estimating the residual asphalt content for a particular gradation and aggregates type. After determining the residual asphalt content by this method, specimens are prepared having a range of residual asphalt contents centered about this estimated optimum and evaluated using the tests given in ASTM D 3910.

Water and Mineral Filler Content: The cone consistency test given in ASTM D 3910 is used to determine the water and mineral filler content. Mineral filler, which can be hydrated lime, cement or stone dust such as limestone dust, may need to be added in an amount from 0.5 to 4 percent by weight of the total mixture. However, this amount of mineral filler is counted as part of the minus No. 200 sieve fraction of the aggregates gradation. Consistency and homogeneity, as represented by the amount of segregation of the mixture, is observed in the cone consistency test. The final water content and mineral filler required is determined by a trial and error process of testing using combinations of the components.

Wet Track Abrasion Test: Samples having the proper amount of asphalt emulsion, mineral filler and water are prepared for testing by wet track abrasion. The *wet track abrasion test* (ASTM D 3910) indicates the wearing qualities of the slurry seal. The amount of material abraded during the test should not exceed 75 grams per square foot. The wet track abrasion test evaluates the combined fine and coarse slurry seal mixture including the aggregates, gradation, mineral filler and emulsion. The emulsion type and formulation has a significant effect on wet track abrasion test results. As a result, the emulsion supplier should be consulted before rejecting an otherwise satisfactory aggregates based on the wet track abrasion test.

Time for Initial Set: If desired, the time for initial set of the slurry seal can be determined by blotting with a white paper towel as described in ASTM D 3910. A cure time also can be determined using the cohesion testing device. In the cohesion test, a rubber foot is rotated in place on a sample of slurry seal at various times after placement. The cure time is defined as the time for the slurry seal to obtain a maximum torque reading. The cohesion testing device is portable and can be taken to the field.

Construction

Slurry Seal Machine: Slurry seal machines are truck or trailer-mounted portable plants. Each unit should have storage for water, emulsion, aggregates and mineral filler. The machine should have an appropriate means for calibrating each component feed device and measuring the amount of each component used. A mixing unit mixes all of the components into a homogeneous product. The mixed slurry is introduced into the slurry box which sits on the pavement. A screw feed distributes the slurry evenly across the width of the box so that the slurry seal is uniformly applied. As the slurry box is pulled over the pavement surface by the slurry truck, the slurry flows under a flexible rubber wiper that squeegees the slurry onto the pavement. As a result, the slurry is essentially the thickness of the maximum size aggregates.

A spray bar may be mounted on the front of the slurry seal machine to apply a fog seal of water for pre-wetting the surface of the pavement. The water fog application can be applied by itself or in combination with a tack coat of diluted emulsion. These applications reduce surface tension and promote coating of the pavement surface by the slurry.

Aggregate: More than one aggregates stockpile may need to be blended to achieve the required gradation for a slurry seal. Aggregates blending should be completed before the slurry seal is placed so that only one aggregates is handled in the slurry seal machine. The stockpile aggregates should be clean with no contamination or oversize material. Because the final surface is applied by squeegee action, oversize particles drag under the squeegee and mar the surface.

Compaction: The quality of an in-place slurry seal and its ability to perform under severe traffic or load conditions depends upon its density. The slurry seal should be compacted to give a low permeability to water and resistance to further densification to traffic. Compaction is applied after the initial set of the slurry seal when it will support the application of a roller without the slurry seal being picked up on the wheels of the roller. A pneumatic roller should be used for the same reasons it is used to compact surface treatments. Another important benefit of rolling at the time of construction is that the slurry seal gains stability at the time of compaction so that the road can be opened to traffic quickly.

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Chapter 16
Non-Construction Uses of Stone

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16.1 Introduction

About 20 percent of the aggregates produced annually in the United States is sold for non-construction use; in agriculture, chemical and metallurgical processing, such as fillers, and for environmental and various miscellaneous applications.[1]

Because of their abundance and desirable chemical properties, limestone and dolomite are most widely used for commercial non-construction applications in the United States. In the words of Charles S. Boynton[2], *"literally any object that exists in a man's home, his office or virtually any product he may use has required limestone or lime in some phase of its manufacture, directly or indirectly, either as a prime or incidental processing material."*

Early Uses: Since antiquity, first lime and then limestone have played major roles in man's existence. The Greeks and Romans were the first to employ lime as a chemical agent, using it for medical purposes and as a bleaching agent for linen. Historical records show that agricultural liming was practiced at about the time of Christ. The use of agricultural limestone or aglime has grown so much that it now comprises over 98 percent of all agricultural liming materials used annually in the United States. Advances in crushing, grinding and sizing technology have created many other new markets for limestone, many of which are discussed in this chapter.[3, 4]

Environmental Applications: National and international concern for protection and conservation of the environment continues to stimulate development of new technologies and applications that utilize limestone and lime. Limestone is employed in the control of sulfate (SO_2) emissions from coal-fired utility and industrial-scale power plants as a means to reduce acid rain. Growth of non-construction markets for stone will continue, with SO_2 emission reduction and other environmental uses very likely leading the way.

16.2 Properties of Limestone for Non-Construction Applications

Limestone is a very broad term. Thirty-eight different types of limestone have been identified, the names of which are based on origin, geology and the crystalline structure of the limestone, the purpose for which it is used, and the impurities present in the rock. Geologically speaking, limestone is a general term for rocks and fossils that contain calcium carbonate ($CaCO_3$), magnesium carbonate ($MgCO_3$) or calcium and magnesium carbonates in varying combinations. The minerals associated with limestone include calcite and aragonite, which are composed of calcium carbonate and dolomite, which is a calcium magnesium carbonate. Occurrence of the minerals in varying proportions causes limestone to be categorized as "high calcium" or "dolomitic." For various limestone types presented in Table 16.1, the nomenclature and approximate composition is given in terms of magnesium oxide (MgO) and magnesium carbonate (MgO_3) content.[5]

Limestone is used for a wide range of both physical and chemical applications because it is stable at normal temperatures and will decompose, or calcine, at high temperatures to produce lime or quick lime, essential ingredients in many chemical and manufacturing processes. The manufacture and use of lime is discussed in detail in the following section.

Table 16.1 Limestone Classification by Mg, MgO and $MgCO_3$ Content[5]

Limestone Classification	Magnesium Content As:		
	Mg	MgO	$MgCO_3$
Dolomite	11.7-13.1	19.4-21.7	40.7-45.6
Calcitic Dolomite	6.5-11.7	10.8-19.4	22.6-40.7
Dolomitic Limestone	1.3-6.5	2.2-10.8	4.5-22.6
Magnesium Limestone	0.6-1.3	1.0-2.2	2.1-4.5
High Calcium	0-0.6	0-1.0	0-2.1

16.3 Lime Manufacture

The use of limestone to manufacture lime represents the second largest market for limestone, exceeded only by the tonnage consumed in the manufacture of portland cement.[1] Due to its high reactivity and enhanced ability to neutralize acidity; lime is used in a wide range of industrial and chemical processes. For example, lime is employed in food processing, water treatment, sulfur dioxide (SO_2) emission control and neutralization of coal mining and industrial wastes. Several excellent references are available that describe the manufacture and utilization of lime.[2, 21]

A unique property of limestone is its calcination at high temperatures. Calcination involves the thermal decomposition of high calcium or dolomitic limestone. Decomposition causes the expulsion of carbon dioxide (CO_2) from calcium carbonate and magnesium carbonate to produce high calcium or dolomitic lime. A significant portion of this production is then rehydrated or *slaked* by the addition of water to produce forms of lime that are easier to handle and use in various chemical and industrial applications. Hydration does not enhance the chemical value of lime. The water added serves as a diluent, and causes only a change in the physical state to improve its handling properties for various applications. Several important facts concerning these chemical reactions are worth noting:

- They are reversible reactions.
- Expulsion of carbon dioxide (CO_2) from the calcium and magnesium carbonate and its complete removal from the system during calcination must occur for the calcination process to be complete.
- Limestone loses weight during thermal decomposition due to expulsion of CO_2. The weight loss, which is termed loss on ignition or LOI, may approach 52 percent or more for pure dolomite, 44 percent for pure calcite, or values between these two extremes depending upon the chemical composition of the particular stone.

- For calcination to occur, limestone must be heated to the required disassociation temperature of approximately 1,700° F. The kiln temperature must then be maintained for a prescribed length of time to prevent over- or under-burning. For calcite, the temperature must be 1,648° F; for dolomite, 786-896° F.

Vertical and rotary type kilns are usually used to manufacture lime. The vertical type kiln is probably the most widely employed worldwide. In the United States, however, the rotary kiln, which is illustrated in Figure 16.1, is used for over 85 percent of the lime produced for direct sale and over 75 percent of the lime produced for the manufacturer's own use.

Figure 16.1 A Rotary limestone kiln.

Forms of Lime or Quicklime

Lump Lime: *Lump Lime* is produced in vertical kilns. The typical mesh size of lump lime is 2.5 x 12 inches, but it may be graded into more restricted sizes: 3 x 6 inches, 4 x 8 inches, 6 x 10 inches, etc.

Pebble Lime: *Pebble lime* was originally produced in rotary kilns, but is now available from vertical kilns that crush and size lump lime to these specifications. It also is produced by certain kilns as a primary product. The typical mesh size of pebble lime is 0.5 x 2.5 inches, but it may be graded to specific mesh sizes such as 0.25 x 0.5 inches, 0.5 x 1.0 inches, 1 x 1.75 inches, etc.

Ground Lime: *Ground lime* is a secondary product of vertical, rotary and special kilns. Ground lime is obtained by screening off fines or is produced as a result of grinding and screening coarser sizes. Its typical gradation: approximately 100 percent passing the No. 8 sieve with 2 to 4 percent passing the No. 100 sieve.

Pulverized Lime: *Pulverized lime* is a secondary product of all kiln types and is produced by pulverization and classification. Its typical gradation is: 100 percent passing the No. 20 sieve to 85 to 95 percent passing the No. 100 sieve.

Briquette (Pelletized) Lime: *Briquette lime* is produced by compressing lime fines into pellets using specially designed molding equipment. Typically the size of briquette lime is approximately one inch. Uniformity is obtained mechanically. The only advantage of pelletized lime over other forms is its uniform physical size.

Product Specifications: Official specifications do not exist for limestone used as kiln feed in the production of lime. Lime producers, however, usually require limestone to meet these requirements:

1. The limestone must be of a high purity. Stone containing 95 percent or more total carbonates is preferred. Many limestone test at over 96 percent total carbonates, with over 50 percent of this falling in the 97 to 99 percent total carbonate range.
2. A stone having a minimum amount of impurities is preferred. Silica, aluminum, iron, phosphorous and sulfur, listed in order of decreasing concentration in limestone, are the impurities of major concern to the lime producer.
3. There are no standard specifications defining the gradation of limestone used as kiln feed stock. Gradation varies for each situation depending upon the type of kiln involved and the manufacturer preference. Size requirements vary from as large as 6 to 8 inches for a vertical kiln to 0.25 to 2.5 inches for a rotary type.

16.4 Agriculture

Agricultural use of limestone has grown significantly since the early 20th century. Agriculture has historically provided a stable second business for limestone producers located within competitive access to agricultural markets. Major agricultural uses of limestone include its direct application as aglime to correct soil acidity, as a fertilizer filler or conditioner as an ingredient in mineral livestock feeds, and as poultry grit.[1, 2]

Direct Application

The direct application of aglime to the soil to correct soil acidity continues to be the largest single non-construction use of limestone in agriculture. Direct application usually consists of applying the limestone with a spreader similar to the one shown in Figure 16.2. Until about 1918, burnt lime was the principal material used for this purpose. Before this time rock crushers were operated by water power, which limited both production and the geographic spread of limestone usage in agriculture in the United States. Since the advent in the 1920s of engines to power rock crushers, the practice of agricultural liming spread widely. Farmers now apply aglime on a regular basis in the area of the country east of a line that runs approximately south from western

Minnesota through Nebraska and Kansas into east central Texas. Aglime also is used in certain high rainfall coastal areas of Washington, Oregon and California .

Figure 16.2 Aglime being applied using a spreader equipped with floater tires.

The Role of Federal Government: The federal government was a major factor in the adoption of the practice of liming by farmers. During the 1920s, the U.S. Department of Agriculture, through the Cooperative Extension Service, mounted a vigorous educational campaign to inform farmers about the benefits of liming. In 1936, U.S. Congress established the Agricultural Conservation Program (ACP) which was administered by the Agricultural Stabilization and Conservation Service of the U.S. Department of Agriculture. It authorized and provided funds for federal sharing with the farmer of the cost of liming materials and spreading services. The ACP program remained in effect from 1936 until 1973 when the program was terminated. The assumption was apparently made by the U.S. Congress that farmers had been educated to the benefits of liming and would continue the practice without the need for further federal incentives. The peak usage of agricultural limestone occurred in 1976 when the amount applied reached a national total of 37.4 million tons. Since then, several factors have adversely affected the U.S. farm economy, causing the production of aglime to level off. These factors include the Russian grain embargo of 1980 and the enactment in 1982 of the Conservation Reserve Program which was designed to take marginal crop land out of production.[2, 3, 6]

Natural Changes in Soil pH

The natural tendency of many soils, particularly in areas of moderate to heavy rainfall, is to become acid with time. If allowed to continue unchecked, this process can result in acid-soil conditions severe enough to significantly reduce crop yields and farm income. Excess soil acidity is one of the most widespread and frequently overlooked agricultural problems in the United States. Many factors, both natural and those resulting from man's activities, contribute to soil acidity. These factors include leaching, erosion, acid precipitation, growing crops and nitrogen fertilizers.

Leaching: *Leaching* is the process by which soil bases, especially calcium and magnesium, are removed from the surfaces of soil particles by the action of downward moving water. This downward flowing water contains weak carbonic and organic acids leached out of the root zone. The sites on the soil particles vacated by calcium and magnesium are reoccupied by hydrogen, which is the agent responsible for soil acidity.[7, 8]

Erosion: *Erosion* is the physical removal of surface soil containing calcium, magnesium, and other nutrients by the action of wind and water. Physical removal of the surface soil in this manner exposes the underlying layers of topsoil and subsoil which may be more acidic and hence detrimental to future crops.[8]

Acid Precipitation: Natural precipitation in all forms, such as rain, snow, etc., is acid. Precipitation typically varies in pH from as high as 5.5 to 5.7, which is defined by scientists as the natural residual pH of precipitation, to as low as 4.0 to 4.5. The pH level depends upon the degree of contamination with sulfur dioxide and nitrogen oxide emissions' produced by coal-burning utilities and industrial plants, motor vehicles, and other sources. Other airborne pollutants or aerosols also lower the pH of precipitation. The cumulative effect of acid precipitation, which is frequently referred to as acid rain, is to increase the acidity of soil and surface waters. Although acid rain contains nitrogen and sulfur which are beneficial crop nutrients, it contributes to soil acidity and its effects on agricultural soils and the environment in general must be monitored.[7, 8,10,11,13]

Growing Crops: Growing crops contribute to soil acidity by annually removing significant quantities of calcium and magnesium from the soil. The actual amounts removed vary due to different calcium and magnesium requirements among various crops. As a rule legumes, especially alfalfa, require greater quantities of calcium and magnesium than corn, most other grains and the specialty or horticultural crops. Crops harvested from the ground up remove more calcium, magnesium, and other nutrients from the ground than those harvested for a specific plant part, such as corn stalks taken for silage compared to removing only the ears. Table 16.2 gives the estimated Ca and Mg removal rates for some common crops.[9]

Table 16.2 Pounds Per Acre of Calcium and Magnesium in Some Common Crops

Crop		Yield	Ca	Mg
			Pounds per Acre	
Alfalfa		4 tons	112	21
Corn	(grain)	150 bus	16	20
	(stover)	4.5 tons	28	17
	Total		44	37
Oats	(grain)	80 bus	2	3
	(straw)	2 tons	8	8
	Total		10	11
Soybeans	(grain)	40 bus	7	7
Wheat	(grain)	40 bus	1	6
	(straw)		6	3
	Total		7	9

Nitrogen Fertilizers: Nitrogen fertilizers contribute to soil acidity in two ways. First, when applied to the soil, ammonia (NH_3) is converted to nitrate nitrogen (NO_3) through a two-stage bacterial process called nitrification:

$$NH_4 + O_2 + \text{(bacterial action)}^{®}\ \text{Æ}\ NO_3 + 4H \qquad (16\text{-}1)$$

An effect of this reaction is the release of free hydrogen into the soil environment which causes an increase in soil acidity. Also, the nitrate nitrogen produced, if not utilized by the crop, forms compounds with calcium and magnesium, carrying them out of the root zone, further aggravating the soil acidity problem.[6]

The Benefits of Liming: The acid soil conditions caused by these phenomena can be effectively neutralized and soil pH maintained at agronomically acceptable levels by regularly applying agricultural limestone. Liming and soil pH correction produce many *agronomic* benefits that readily translate to increased crop yields:

1. Liming stimulates soil microbial activity, which increases the breakdown and availability of nutrients in soil organic matter. Nitrogen fixation by the action of nodule bacteria on the roots of legumes (alfalfa, soybeans, etc.) increases the yield for these crops as the pH increases due to liming.[9]
2. Liming improves soil tilth or physical condition, facilitating tillage operations. The calcium and magnesium in limestone exert a flocculating effect on many soils making them more workable, which is an important consideration with regard to hard-to-work soils high in clay content. Soil drainage also is enhanced when tilth is improved.[9]
3. Fertile, well-limed soil supports heavier plant growth and more extensive root development. On soils dedicated to intensive crop production, this translates to greater accumulation of organic matter, a major factor in both soil fertility and tilth.[2]

4. Liming increases the efficiency of high-cost fertilizers by contributing to a favorable soil environment for plant growth and for maximum utilization of applied fertilizer nutrients. Phosphorous, one of the three primary fertilizer nutrients is especially sensitive to pH, steadily increasing in availability up to a pH of 6.5 to 7.0. *Agronomists generally agree that, for many soils, a pH of 6.5 to 6.9 is optimum from the standpoint of availability of all plant nutrients important in crop nutrition.*[7,9]

Soil Testing

Agricultural limestone should be applied to cropland only after the area to be treated has been sampled, tested and the aglime requirement determined by a reputable university or commercial soil testing laboratory. Routine soil tests are inexpensive and provide essential information on soil acidity, the required rate of aglime to apply, and other soil data, including fertilizer application rate, needed in planning a total soil fertility program. The millions of soil samples analyzed in the United States each year attest to the importance of soil testing in American agriculture. For those farmers who sample the soil annually and follow liming recommendations, the pay-off is higher yields and increased profits.[3, 8, 12]

Aglime Quality

The total effectiveness of agricultural limestone is a function of its chemical composition and physical properties, i.e., its purity and fineness of grind (or gradation).

Purity: Purity is determined by the calcium and magnesium content of limestone. It is expressed in several different ways in the laws and regulations for liming materials in the various states. Calcium carbonate equivalence (CCE) is the most widely used measure of purity and neutralizing value (effectiveness) of liming materials. CCE is defined as the acid neutralizing capacity and is expressed as a percent by weight of calcium carbonate. To determine CCE, the values for elemental calcium (Ca) and magnesium (Mg), calcium and magnesium oxide (CaO, MgO), and magnesium carbonate ($MgCO_3$) must be converted to an equivalent calcium carbonate value. Table 16.3 lists the conversion factors used for these calculations.[3, 6]

Table 16.3 Calcium Carbonate (CCE) Conversion Factors[6]

Ca to $CaCO_3$	Ca% x 2.50
Mg to $CaCO_3$	Mg% x 4.12
CaO to $CaCO_3$	CaO% x 1.78
MgO to $CaCO_3$	MgO% x 2.48
$MgCO_3$ to $CaCO_3$	$MgCO_3$% x 1.18

If the analysis of a particular limestone is 26 percent elemental calcium (conversion factor 2.5) and 6 percent elemental magnesium (conversion factor 2.5), its calcium carbonate equivalence is 89.72 percent. Table 16.4 lists the CCE values for calcitic and dolomitic limestone and several other liming materials. The presence of impurities in any liming material reduces its neutralizing value (CCE). For example, the CCE value for marl (70-90), which is typically high in clay content, is low relative to the other materials listed.[4]

Table 16.4 Relative Neutralizing Values Expressed as Percent CCE of Some Common Liming Materials[3]

Material	Composition	CCE
Pure Calcite	$CaCO_3$	100
Pure Dolomite	$CaMg(CO_3)_2$	108
Burned Lime	CaO	150-179
Hydrated Lime	$Ca(HO)_2$	120-146
Marl	$CaCO_3$	70-90
Burnt Oyster Shells	CaO	90-110

Table 16.5 Mechanical Analysis of Limestone from Five Selected Midwestern Quarries[15]

Size Fraction	Quarry Number				
	1	2	3	4	5
Passing 60 Sieve	12.5	18.7	18.9	20.4	22.0
30 to 60 Sieve	6.6	12.6	9.9	14.1	14.2
8 to 30 Sieve	38.6	45.1	36.7	46.2	42.6
Retained on No. 8 Sieve	42.0	23.5	34.3	19.1	21.1

Fineness: *Fineness of grind* (gradation) is the other major quality factor that determines effectiveness. Agricultural limestone or aglime produced by regular crushing procedures has a range of particle sizes, with the upper limit determined by the size of the largest screen used for sieving. Table 16.5 shows the particle size analysis of aglime products from five aglime quarries in central Illinois.[l5]

National gradation standards do not exist for agricultural limestone. Various sieve sizes are employed in specifying gradation by the different states. However, characterization of aglime and other liming materials according to particle size determines the rate of reaction in the soil. As fineness increases and particle size decreases, several important benefits occur: particle surface area, and hence reactive surface area, of the liming materials increases. As a result, the finely divided liming material, when uniformly mixed with the soil, provides more particles per unit of soil volume resulting in less distance between particles and more rapid neutralization of soil acidity.[2, 4]

The interaction of chemical purity and particle fineness determines the quality and effectiveness of limestone. As these properties improve, not only does the liming material react more quickly, but the amount of liming material required achieving the same result decreases. The positive effects of chemical purity and particle fineness on crop response to liming are illustrated in Tables 16.6 and 16.7, respectively

Table 16.6 Tons of Liming Material Required at each CCE Level to Equal One Ton of 100% Calcium Carbonate $CaCO_3$

CCE of Liming Material	Tons Required to Obtain one Ton of 100% of $CaCO_3$
60	1.68
70	1.43
80	1.25
90	1.11
100	1.00
108	0.92

Table 16.7 Relationship Between Limestone Fineness and Crop Yield, Averaged Data, Field Experiments – Midwest[3]

Limestone Fineness (% Passing 60-Sieve)	Limestone Required for Equal Crop response 80 percent Relative Yield (Tons per Acre)
20-30	3.9
31-40	3.0
41-50	2.7
51-60	2.3
61-80	2.1
80	1.8

Product Specifications: National product specifications (standards) for liming material do not exist. Most states where liming is a recommended agricultural practice, however, have specifications which regulate the quality of liming materials sold to the public. These specifications take the form of liming materials laws, or regulations, fertilizer laws or specifications which by law the vendor must guarantee. Certain states, such as Illinois and Indiana, do not have liming materials specifications. Aglime producers in those states control the quality of their product through self-policing programs. Producers in Illinois and Indiana have their product sampled and tested annually, after which the results for calcium carbonate equivalence and fineness are published and made available to the public. Producers can compare the quality of their aglime with the competition, a feature which provides the incentive to produce a high-quality product.

State specifications most frequently are determined by the demands of the marketplace and the geology of the locally available stone. In many states the aglime committee of the state aggregates association works with state officials to develop specifications. In some states the Agricultural Stabilization and Conservation Service (ASCS) establishes specifications that liming materials must meet to qualify for economic assistance or cost-sharing under federal conservation programs. Other states have adopted, all or in part, the American Society for Testing and Materials (ASTM) Specification C 602-Standard Specification For Agricultural Liming Materials. ASTM Specification C 602 is based on the classification of liming materials according to Calcium Carbonate Equivalence (CCE) and percent passing the No. 8 and No. 60 sieves (Table 16.8).[14]

Table 16.8 ASTM Standard Specification C 602 For Agricultural Liming Materials[14]

<table>
<tr><th colspan="3">Chemical and fineness specifications for agricultural liming materials established by ASTM.</th></tr>
<tr><th colspan="3">Chemical Classification of Agriculture Liming Materials</th></tr>
<tr><th>Material</th><th colspan="2">Calcium Carbonate Minimum Equivalent (C, C, E) %</th></tr>
<tr><td>Burnt Lime</td><td colspan="2">140</td></tr>
<tr><td>Hydrated Lime</td><td colspan="2">110</td></tr>
<tr><td>Limestone</td><td colspan="2">80</td></tr>
<tr><td>Slag</td><td colspan="2">80</td></tr>
<tr><td>Shells</td><td colspan="2">80</td></tr>
<tr><th colspan="3">Classification for Agricultural Limestone</th></tr>
<tr><th>Class Designation</th><th>Passing No. 8 (2.36 mm) Sieve, Min. (%)</th><th>Passing No. 60 (250 microns) Sieve, Min. (%)</th></tr>
<tr><td>S</td><td>100</td><td>100</td></tr>
<tr><td>T</td><td>99</td><td>75</td></tr>
<tr><td>O</td><td>95</td><td>55</td></tr>
<tr><td>N</td><td>90</td><td>40</td></tr>
<tr><td>E</td><td>80</td><td>25</td></tr>
</table>

Pelletized Limestone

Pelletized limestone came on the market in the late 1970s. *Pelletized limestone* is made with finely ground limestone (No. 200 sieve or finer). The finely ground limestone is mixed with a water soluble binder such as bentonite clay or lignin liquor, a by-product of the paper industry. Proper control of the binder and water during the pelletizing process produces a limestone pellet with the integrity to withstand degradation during handling but which will readily break down upon application when exposed to moisture. Developing a specification for pelletized limestone is difficult, because to determine the purity and fineness of the limestone present requires its separation from the binding materials. State agricultural laboratories where pelletized limestone is sold have been unsuccessful to date in developing a test procedure for accurately analyzing pelletized limestone.[8]

Initially promoted as a lawn and garden product, pelletized limestone has steadily gained market acceptance since that time. Although the homeowner remains the primary customer, pelletized limestone is now gaining acceptance in some areas as a commercial liming material for agriculture, due to its effectiveness and ease of handling during spreading.

Fluid Lime

The application of aglime in the fluid form has gained acceptance in recent years as better equipment has been developed to handle it. Aglime in the fluid form is referred to as suspension lime and fluid lime. Water is the liquid carrier normally used to formulate fluid or suspension lime mixtures. Nitrogen solutions sometimes are used as the liquid carrier. The use of nitrogen permits the application of nitrogen and aglime in one operation. Herbicides also can be added to the mixture to give it further versatility.

The concept of grinding limestone to extreme fineness for agricultural use was first conceived in the early 1960s to satisfy the need for a liming material capable of reacting rapidly with the soil to produce the desired pH adjustment over a relatively short period of time. Severe dust problems associated with the application of finely divided dry limestone prompted the development of fluid aglime formulations.

The liming agent used in suspensions must have a very fine particle size. To permit good dispersion and suspension throughout the liquid carrier, approximately 100 percent of the material should pass through a No. 100 sieve and a minimum of 80 to 90 percent through a No. 200 sieve. A high CCE limestone is preferred for this purpose.[16, 17]

Some fluid blend fertilizer dealers market fluid aglime-potash suspensions for winter application to utilize both labor and high-cost application equipment during the off-season. Phosphate fertilizers are not mixed with fluid lime suspensions. Insoluble calcium phosphate precipitates may form, which can interfere with the normal operation of the application equipment and render the applied phosphate unavailable to the crop.[9]

Liming Value: The problems of characterizing the physical properties and liming value of fluid lime formulations are similar to those for pelletized lime and involve problems of accurately separating the limestone from its carrier.

Fertilizer Filler

Definition: The American Association of Plant Food Control Officials defines filler as any substance added to fertilizer materials to provide bulk, prevent caking or serve some purpose other than providing essential plant nutrients. Fertilizer blenders use dolomitic limestone for this purpose. Its addition also serves to dilute the mix to the proper analysis, helps to neutralize the effects of acid-forming nitrogen ingredients and helps prevent bag rot sometimes caused by excess acid in the super-phosphate component of fertilizer. Dolomitic limestone is preferred over a high calcium stone to reduce the risk of forming insoluble calcium phosphate compounds.[9, 18]

Example Formulation: Consider a typical example of how dolomitic limestone can be used in formulating a dry fertilizer blend. A farmer places an order with his local fertilizer supplier for five tons of a blended 9-25-20 fertilizer for application to some recently harvested corn land before plowing in the fall. Fertilizer analyses are always stated in terms of percent total weight of primary nutrients in the following order: nitrogen (N), phosphate (P205) and potash (K20). The dealer elects to make up this order using diammonium phosphate (18-46-0), ammonium nitrate (34-0-0), muriate of potash (0-0-60) and dolomite as filler. These are all standard blending materials that are inventoried in bulk. The mixing formula for developing the desired fertilizer blend is given in Table 16.9.

Table 16.9 Fertilizer Formulation

Formulation	Total Material Weight	N	P2O5	K2O
		Ingredient Weight (lb)		
1. Desired blend analysis required for 5-ton batch (lb)				
	—	9	25	20
2. Proposed blend formulation				
18-46-0	4000	720*	1840	0
34-0-0	530	180.2	—	—
0-46-0	1435	—	660.1	—
0-0-60	3335	—	—	2001
Filler	700	—	—	—
Total (lb)	10,000	900.2	2500.1	2001

** This number is obtained by multiplying the total nutrient weight by the component percent expressed as a fraction: 4000 lbs (0.18) = 720 lbs.*

Historical Usage: The use of dolomite and limestone as a filler closely paralleled the growth in mixed fertilizer consumption. Limestone and dolomite usage as a filler increased until the late 1950s, but has gradually decreased since that time due to the advent and increasing use of higher analysis fertilizers that required less filler. The growth in demand for liquid and gaseous forms of fertilizer that do not require filler has further reduced consumption of limestone and dolomite for this purpose.[2]

Product Specification: Standards for the characteristics of fertilizer filler materials are established by the individual companies involved with formulation of the products. At the present time, there are no state or federal standards.

Bulk blending became a commercially important fertilizer marketing technique in about 1958. Studies by the Tennessee Valley Authority and the fertilizer industry have demonstrated that particle size variation among raw materials used in blending is a major cause of the segregation or unmixing of blend components due to handling after mixing and segregation during application in the field. As a result, particle size-matching of blending materials, including filler, has become standard practice in dry blend formulation. Hence, fertilizer blenders in most situations try to obtain dolomite or limestone that gives the closest possible match of particle size with the other blending materials in their inventory.[19]

Granulated fertilizer materials used in the blending range come in particle size distributions of No. 6 to No. 20 sieve and exhibit considerable variation within that range. The filler size should be matched to fall within this sieve range, and preferably have a size representing the greatest percent by weight of the blend. This size filler meets formulation needs in most bulk-blending situations.[2, 19]

Product Specifications: Gradation and particle shape are the physical properties usually given in poultry grit specifications. Particle size specifications usually are provided by the purchaser and range from approximately 0.142 to 0.187 inch (the equivalent of a No. 6 and No. 4 sieve, respectively) all the way up to 0.375-in. Regardless of particle size, poultry grit should have a uniform gradation and fine or coarse material should not be present.[2] Rounded or spherical granules are preferred over elongated or flat ones.

Chemical purity is of secondary importance. Hatcheries prefer carbonate types of poultry grit, probably because the calcium present enhances egg shell formation. Some authorities, however, believe that too much calcium is injurious to poultry and recommend diluting carbonate type grit with non-carbonate siliceous materials such as granite.[2]

No-tillage and Minimum Tillage Practices

No-tillage or *minimum tillage* practices involve reducing or eliminating vehicle movement for crop cultivation. Reduced tillage practices have many advantages where the crop residue improves soil tilth. A reduction in the number of trips across a field reduces soil compaction and as a result improves plant growth. The soil pH requires more attention in the planning phase when going to reduced tillage. The soil below a depth of 2 inches cannot be effectively limed from the surface without tilling the soil and mixing in the aglime. Therefore, the soil must be at the target pH levels throughout the root zone before reduced tillage commences. The surface pH also is critical in reduced tillage fields. The use of pesticides and herbicides is generally greater when reduced tillage is used. A surface pH of 6 or higher is required for the herbicide to be most effective.

Miscellaneous Uses

Turf and Lawns: The use of aglime for turf and lawn applications represents one of the single largest markets in the United States, outside of commercial agriculture. More than 5 million tons of aglime are used annually for the establishment and maintenance of millions of acres of turf and lawns in public recreation areas, landscaping around office and apartment building complexes, university and public school grounds, erosion control, landscaping of highways and the millions of single-family homes in the United States. Over 13,000 golf courses across the country alone comprise over two million acres of turf that require regular annual applications of fertilizer and aglime.

Turf and lawn liming recommendations vary from state to state, depending upon climate, soil types of each area, and the species of grass to be grown. To properly lime a lawn or turf, the soil should first be sampled and analyzed. The recommendations given on the soil test report should be followed closely. The county agricultural extension agent is also a valuable source of recommendations for the care of lawns and turf.

Tree Liming: Orchard trees represent a significant but relatively untapped market for agricultural limestone.[2]

Lake and Watershed Liming

The effects of acid rain on fresh water lakes and their surrounding watersheds was first recognized in northwestern Europe in the early 1950s and in eastern and northeastern North America in 1957. The acidification of surface fresh water bodies continues to receive considerable attention, including numerous research studies in the eastern United States, Canada and Scandinavia where the problem persists and has worsened in some areas.

New York and Massachusetts, which have significant problems with surface water acidification, have established programs to fund mitigation efforts. The Adirondack region of New York, which is rich in pristine lakes, has become a laboratory for the study of surface water acidification and lake liming techniques. A considerable amount of our knowledge concerning the causes and effects of the acidification phenomenon has been developed from research conducted in this area.[27]

Neither federal nor state governments participate in the commercial implementation of lake liming activities. They have deferred this task to the private sector. The lake and stream liming research program that the Fish and Wildlife Service now has in place was organized and implemented by private consulting firms having expertise in this field.[29, 30]

Methods and Rates of Application: Lake liming materials are commonly applied as slurry, although the dry form can be used. Liming application is accomplished using a boat or barge equipped with the necessary mixing tanks, pumps, and space for liming material storage. Figure 16.3 illustrates lake liming treatment in progress. A helicopter, similarly equipped, is used for treating lakes and streams not accessible by land.

Courtesy Timothy B. Adams and Associates

Figure 16.3 Limestone being applied in slurry form to a lake using a barge equipped with a boom-type applicator.

Table 16.10 Lime Requirements of Pond Muds Based on pH and Texture[32]

Mud pH*	Heavy Loams or Clays	Sandy Loams	Sand
< 4.0	12,800	6,400	4,000
4.0 – 4.5	9,600	4,800	4,000
4.6 – 5.0	8,000	4,000	3,200
5.1 – 5.5	4,800	3,200	1,600
5.6 – 6.0	3,200	1,600	800
6.1 – 6.5	1,600	1,600	0
> 6.5	0	0	0

** The pH is measured in a 1:1 mixture of dry, pulverized mud and distilled water.*

A lake liming program normally begins with the collection and analysis of mud samples from the lake or pond bottom. Application rates are given in Table 16.10 and are based on the pH and clay and organic matter content of the mud. Application rates typically vary from 1,000 to over 10,000 pounds per acre of surface area. Agricultural limestone or slag (the non-metallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace) are the only materials that safely can be applied at these rates to ponds containing fish. Hydrated lime or calcium oxide (CaO) can only be applied at rates of 250 to 300 pounds per acre without endangering the ecology of the water body.[32, 33]

Product Specifications: National standards or specifications have not been developed for liming materials used for lakes and streams. Alkaline materials of high chemical purity perform best. Liming materials meeting this requirement include high-calcium and dolomitic aglime, dry and hydrated calcitic and dolomitic lime, basic slag and liquid lime. These materials vary widely in gradation from very fine minus 200 mesh material, through the normal range of aglime material, to large, pebble-sized limestone used for liming streams.[32, 33]

For pond and watershed liming, aglime appears to perform best. Aglime has the same long-term effect when applied for this purpose as when applied to soil to neutralize acidity, due to the range of particle sizes employed. Very fine minus No. 100 sieve size material provides almost immediate neutralizing action while the coarser fractions greater than the No. 60 size mesh provide a long-term neutralizing effect. The criteria previously discussed to evaluate agricultural liming material also can be used to evaluate aglime for lake, river and watershed applications; fineness of grind, chemical purity and calcium carbonate equivalent (CCE) are all important.[32]

16.5 Environmental Applications

Stack Gas Desulfurization

Environmental Applications: Since the 1960s efforts have been underway to develop the most effective technology for removing undesirable combustion products from stack exhausts to avoid releasing them to the atmosphere. *Stack-gas desulfurization* is the collective term used to describe the processes involving removal of sulfur dioxide (SO_2) from stack exhausts. The industries most concerned with stack gas desulfurization include coal-fired utilities and various private industries that use coal as a primary source of fuel. Many approaches are used for stack-gas desulfurization. These approaches employ limestone either alone or in combination with other sorbent materials. Limestone specifications vary depending upon the technology or strategy used.[22]

Pre-combustion or *pre-flame clean-up* includes any measure taken prior to the point of combustion, including mechanical or chemical cleaning of coal to change the material from a high sulfur to a low sulfur coal or other low sulfur fuel. This process is called *coal switching*. Coal switching techniques do not involve use of limestone or other sorbent materials.[23, 25]

In-Flame Clean-Up: *In-flame clean-up*, also called in-situ clean-up, involves desulfurization of the coal gas as combustion takes place. In-flame clean-up is accomplished by bringing the coal and limestone sorbent into intimate contact with one another to achieve desulfurization and sulfur capture as the combustion gases are being produced.[23]

Three different types of *fluidized bed combustion* systems are used, with each having slightly different limestone sorbent requirements. Fluidized bed combustion (FBC) is probably the best known technology of the "in-flame" category. Atmospheric fluidized bed combustion (AFBC) has been utilized for several years on small industrial power plants of less than 80-megawatt capacity. Passage of Clean Air legislation has added further effort to this development process. FBC is desirable because of its:

- Low capital cost;
- Suitability as a retrofit technology for existing power plants;
- High $S0_2$ capture efficiency; and
- Other special features associated with this technology.

Figure 16.4 Tennessee Valley Authority Shawnee Power Plant, Paducah, KY, retrofitted with demonstration-scale fluidized bed combustion broiler (left end).

In the fluidized bed desulfurization process, a bed comprised of a mixture of crushed coal and limestone is suspended on a bed of air produced by jet-air blasts issuing from the base of the boiler chamber. This causes the coal-limestone bed to levitate and take on the appearance of a boiling fluid.

Atmospheric Fluidized Bed Combustion: AFBC operates at atmospheric pressure. Figure 16.4 illustrates a demonstration scale AFBC system. Limestone with a fine grain crystalline structure and crushed to a No. 6 to No. 20 sieve size are preferred, since they provide the necessary reactive surface area for maximum sulfur capture. A high purity limestone having in excess of 90 percent calcium carbonate is usually specified for use in these systems. Research and operating experience, however, have demonstrated that dolomitic stone is also an effective AFBC sorbent. Although magnesium does not enter into the sulfur capture process, the magnesium carbonate present in the original stone calcine to produce magnesium oxide and is thought to add to the porosity and reactive surface area of the stone.[23]

Very soft stones deteriorate too rapidly and are elutriated from the system, allowing calcium to leave the bed. Hard stones do not calcine rapidly enough, reducing their potential efficiency. Use of limestone of improper hardness in AFBC systems requires greater quantities of stone to accomplish the same objective, reducing both the chemical and economic efficiency of the operation.[25]

Circulating Fluidized Bed Combustion: Circulating fluidized bed combustion (CFBC) is comparable to AFBC since it also operates at atmospheric pressure.[28, 30] In contrast to the AFBC process; it involves forcing air and entrained gases of combustion through the fluidized bed at high velocities (50 to 300 fps) to achieve high solid recirculation through the system. The solids are separated from the circulating air and gases in a series of one or more cyclones. The solids are continuously returned to the fluidized bed through a recycle loop. This technique results in SO_2 capture efficiency as high as 92 to 95 percent. Also, the quantity of coal and limestone required for this process is reduced compared with AFBC.[23]

Limestone used in circulating bed systems, similar to AFBC systems, should be of high purity, porous, and possess a fine grain crystalline structure. Dolomitic limestone works well in both CFBC and AFBC systems. Gradation of the dolomitic limestone used in CFBC systems should be on the order of the No. 16 sieve to the No. 100 sieve or the No. 70 sieve to the No. 200 sieve compared with the coarser No. 6 to No. 20 sieve gradation specified for AFBC systems. Both softer and harder stones can be utilized more effectively in CFBC systems as compared to AFBC systems.[24]

Pressurized Fluidized Bed Combustion: The PFBC system is an adaptation to pressurized conditions of the AFBC and CFBC technologies. Both bench and pilot scale research has demonstrated that pressurized fluidized bed boilers achieve the same generating capacity as AFBC and CFBC systems at a considerably greater efficiency. The PFBC process uses smaller boilers, less fuel, and less sorbent compared to the other two processes. Under full-scale operating conditions, this results in significant savings to utilities equipped with this technology. The physical and chemical properties of the stone and the fineness of the grind are similar to those for the AFBC system except that dolomitic limestone is the preferred sorbent.[2, 24]

Industrial CFBC units became commercially available during the 1980s. Progress in research and development suggests utility sized CFBCs along with utility and industrial-sized PFBC systems may be available in the mid-to-late 1990s. From the perspective of the stone producer, these will be significant events in view of the fact that limestone is the sorbent of choice for these technologies.

Post-Flame Clean-Up: *Post-flame clean-up* is the removal of SO_2 downstream from the boiler. All post-flame systems employ scrubbing technology, which in the utility industry is called *flue gas desulfurization* (FGD). In FGD systems, coal combustion gases are exposed to alkaline sorbents, either in the wet or dry form, at some point in the exhaust line between the boiler and the stack. All FGD systems are identified according to whether they are wet or dry and non-regenerative or regenerative. The *wet or dry* designation indicates the form in which the sorbent is used. *Non-regenerative* or *regenerative* designates whether the spent sorbent is disposed of as waste or processed to recover sulfuric acid and sulfur for resale. Of the nearly 200 types of FGD systems identified by the Electric Power Research Institute, wet limestone/lime, non-regenerative systems comprise over 85 percent of the units presently operating at utility power plants. Spray drying and all-dry systems make up the remainder.[23, 26]

Wet Scrubbing Systems: In wet scrubbing an alkaline agent, usually lime and/or limestone, is mixed with water to form a slurry and then sprayed into the flue gases in a spray chamber or absorber downstream from the boiler. The SO_2 is absorbed into the slurry where it reacts with the limestone and lime to form calcium sulfite and/or calcium sulfate (gypsum). This gypsum slurry is then precipitated out and removed.

Spray Drying Systems: In spray drying systems, the sorbent enters the absorber as a wet slurry and dried in the absorber by hot gas. As drying takes place, the slurry reacts to capture the SO_2. The dry product is then collected at the bottom of the absorber and removed.

All Dry Operation: In the all-dry operation, the sorbent in dry form is injected into the duct work ahead of the bag house and then collects on a fabric filter. Sulfur dioxide (SO_2) capture occurs as the flue gas passes through the fabric filter. The filter cake is then collected and removed.

Specifications: Specifications for sorbent used in FGD systems are typically much more stringent than are those for limestone used in the FBC process. High calcium limestone is preferred, consisting of 95 percent or more $CaCO_3$ with 100 percent passing the No. 20 sieve and 80 percent passing the No. 325 sieve. The product should have a magnesium content of less than 1 to 2 percent, with other impurities being less than 0.03 percent. Normally, however, utilities using FGD systems require limestone to be ground to approximately a minus ¼-in. size particle gradation. The better storage and handling qualities of the coarser ground stone permits stockpiling and then grinding by the utility to specification at a later time.[4]

Acid Mine Drainage Abatement

Acid mine drainage is a pollution problem resulting from the oxidation of pyrite (FeS_2) present in mine wastes. Oxidation produces sulfuric acid (H_2S0_4) and other strong acids which can create extremely low pH conditions. Acid mine drainage is primarily associated with the mining and cleaning of coal and other sulfide minerals. If not properly treated, the leachate and resulting acid discharge kills vegetation and fish, contaminates ground water and in general negatively affects the environment for many years following cessation of mining operations.[34, 35]

The basic technology of acid mine drainage abatement has not changed in many years. Two proven approaches still dominate the field and frequently are used in combination.[36]

Treatment of Process Water: Lime treatment of process water is a common method of treatment in anthracite coal washing plants and impounded acid drainage from active and abandoned coal mines. Treatment neutralizes the acidity and removes heavy metals, especially iron. These steps are necessary to reclaim the effluent for reuse or assure it meets water quality standards required for release into the environment. Most anthracite coal mining operations are equipped with an acid neutralization system for this purpose.[35]

Some mines use only high-purity limestone for neutralization. Other mines use lime in combination with pulverized limestone, which is commonly referred to as a split limestone-lime treatment. In a two-step treatment process, acid mine drainage waters are first treated with finely ground limestone, which raises the pH to between 5.0 and 6.0, causing ferric iron (Fe^{+3}) to precipitate out. Lime is then added to complete the neutralization process by raising the pH to about 9.0 and precipitating out the ferrous iron (Fe^{+2}) present. Ferric and ferrous iron are the heavy metal constituents present in the greatest amounts and are of primary environmental concern in the mining process and drainage of acid water from the mine.[38]

Lime and limestone complement one another in the neutralization process. Lime is the more reactive of the two materials. It has the capability to neutralize strong acid well into the strongly alkaline pH range (a pH of 9.0 or more). This high pH causes the precipitation and removal of ferrous iron (Fe^{+2}), which usually requires a pH of 8.5 to 9.5.[36]

Hazards of Lime Treatment: Lime is a high-cost material and has a tendency to produce large volumes of fine sludge. Streams and stream life may be adversely affected by accidental over-treatment. Because lime is caustic, a hazard always exists for operating personnel handling the material. Limestone, which is the less reactive of the two materials, is most effective as an acid neutralizing agent in a pH range of up to about 6.0. Limestone, however, is desirable as a neutralizer because of ease of handling, effectiveness as a neutralizing agent on the acid side of the pH scale, and its production of lower volumes of fine sludge.[35]

Other Treatment Materials: Other materials, such as caustic soda, soda ash and magnesium oxide, also are used to treat coal mine process and acid waters. In addition, various manufactured products have been developed and are in use. Lime and limestone, however, continue to dominate this market.[37, 39]

Product Specifications: Particle fineness and high chemical purity are the key to the effectiveness of materials used for this purpose. Coal mine operators prefer a lime or limestone with a fineness in the minus No. 200 (75 µm) sieve size to submicron size, and a calcium and magnesium carbonate content in excess of 95 percent. Both high-calcium and dolomitic limestone, and calcitic and dolomitic limes are used for this purpose.[2]

Treatment of Coal Refuse

Pyrite present in coal debris left behind in the mine, in spoil piles produced during coal cleaning operations, and in disturbed overburden produces sulfuric acid (H_2S0_4) and other strong acids when exposed to atmospheric oxidation. Coal mining refuse includes the disturbed overburden and the spoil piles produced during coal cleaning operations, and represents the other major source of acid mine drainage that must be treated at a typical coal mine site. Federal and state laws prescribe how to dispose of these wastes. Generally disposal involves reclamation techniques that include forming and reshaping the disturbed overburden and spoil piles, treating them with an acid neutralizing agent, covering the area with top soil, and where possible re-establishing vegetation. Usually agricultural limestone is employed at very high rates, frequently in excess of 100 tons per acre.

Product Specifications: National specifications do not exist for limestone or lime used for the treatment of coal refuses. Applicable specifications for gradation and chemical purity of agricultural limestone should be used.

Landfill Construction

The use of crushed limestone is an effective, low-cost approach for precipitating out certain heavy metals that would otherwise migrate from solid waste in landfills with the leachate. Agricultural limestone is regarded as particularly attractive for this purpose because of its wide geographic distribution, particle sizes and relatively low cost.

Sandwiching landfill between layers of limestone is preferred to mixing limestone with soil. Intimate mixing results in soil stabilization which initially prevents the leachate solution from leaving the site. Eventually, however, soil stabilization encourages the formation of fixed channels or holes in the landfill through which leachate freely flows into the surrounding soil. The effective life of the limestone may also be shortened if the soil is acid.[40]

Product Specifications: Agricultural limestone specifications can be used for limestone employed in landfill construction.[2]

Four distinct uses exist for aggregate fines in landfills:

1. Limestone is used to treat the acid drainage from the landfill.
2. Any aggregates, with sufficient permeability, is used to provide drainage and collection of methane.
3. An aggregates cushion is used to protect the landfill liner. Frequently, use of a limestone is not recommended because of the fear that acid drainage will react with the limestone causing it to soften and/or dissolve over time.
4. Aggregates are frequently used in the daily cover material (used to protect newly deposited refuse from scavengers) and in the final capping layer.

On-site Residential Sewage Systems

NASA, through a contract with the University of West Virginia, has developed a residential sewage system that uses an underground box of rocks with appropriate plant growth above. The plants digest the sewage and clear water leaves the lower end. Others have developed similar systems.

Drain fields for septic systems have used stone of various sizes for many years. This basic system uses a combination of plant growth and evaporation to disperse the liquids while the solids are kept in the septic tank.

16.6 Chemical and Industrial Processing

Portland Cement Manufacture

Over one hundred plants are in operation in the United States which manufacture portland cement. None of the plants use precisely the same combination of raw materials. More than 80 percent of the raw materials, however, used in the kiln feed formulations at most of these plants are limestone. Over 100 million tons of limestone are used annually in the manufacture of portland cement.[1]

Table 16.11 Partial List of Raw Materials Used to Make Portland Cement[2]

Oyster Shell	Kaolin
Clay	Sand
Limestone	Quartzite
Coquina Shell	Iron Pyrite
Shale	Traprock
Marl	Fuller's Earth
Chalk	Iron Oxide
Slag	Blast-Furnace Slag Dust
Marble	Gypsum

Portland cement is a manufactured product produced by blending different natural and synthetic ingredients to achieve precise chemical proportions of lime, silica, aluminum and sulfate in the finished product. The manufacturing process involves three basic steps: (1) proportioning of the raw materials, (2) burning and (3) finish grading.

Proportioning of the Raw Materials: Preparation of the kiln feed formulation first involves mixing the ingredients in the desired proportions to form a homogeneous mixture. Then the formulation is wet or dry ground to reduce it to the required gradation for feeding into the kiln. Early cements were made from two-component mixes. In recent years, due to the many types of concrete required in the marketplace, three- and four-component cements have become the standard. The ingredients used to make portland cement at any given plant are usually determined by the geographic location and the availability of raw materials.

Burning: Burning is the conversion of the properly designed kiln feed mix into clinker. Burning is performed under controlled combustion conditions. Subsequent quenching and cooling of the clinker is conducted to obtain the required qualities of the ultimate product. The clinkering process is carried out in refractory lined rotary kilns.

Finish Grading: Finish grading is the fine grinding of the clinker end-product to produce a fine gray powder referred to as portland cement.[2, 41]

Product Specifications: The only rigid requirement for the limestone used in producing portland cement is that the raw material should contain 3 percent or less magnesium carbonate. This requirement on the magnesium carbonate content is necessary to satisfy commercial specifications for finished portland cement, which usually requires a maximum of 6 percent magnesium oxide (MgO). Otherwise, there are no specifications as to purity. High calcium and metallurgical grades as well as other relatively impure high calcium stones low in MgO are generally acceptable for portland cement manufacture.

Glass Manufacture

Limestone also is used in the manufacture of glass. Figure 16.5 shows glass bottles, manufactured using limestone, moving down a production line.

Figure 16.5 Glass bottle manufacturing using limestone.

Almost all glass produced contains three constituents: (1) formers, (2) fluxes and modifiers and (3) stabilizers or intermediates.

Formers: *Formers* are substances that give glass its characteristic appearance and non-crystalline structure. Silica or silicon dioxide (SiO_2) is the principle ingredient used in the production of most commercial glass today. In addition to silica, the oxides of boron, phosphorous, germanium and arsenic are sometimes used as formers. Many of the different type glasses made using these materials possess specialized optical properties.

Fluxes or Modifiers: Fluxes and modifiers form a mixture with the silica and serve to lower the melting point of the silica. Common flux materials include the oxides of sodium, germanium and lithium.

Stabilizers or Intermediates: *Stabilizers*, sometimes referred to as *intermediates*, are substances added to the silica-flux mixture to give it stability. Glass composed of only silica and flux is chemically unstable. High-calcium and dolomitic limestone and their derivative limes are used interchangeably as stabilizers. The glass making industry has shown a clear preference for limestone compared to lime in recent years, as indicated by tonnage consumption trends for these two materials.[2]

The purpose of calcium and magnesium, whether added as limestone or lime, is to (1) make the glass more insoluble so that it can be used in contact with water and chemical solutions, (2) improve its mechanical properties by making the glass stronger and less brittle and (3) improve its appearance. Both dolomitic and high-calcium limestone are used to make plate, window or flat glass, although about three times as much dolomitic as high-calcium limestone is used for this purpose. Dolomitic stone also is preferred for making glass containers of various types due to resistance to the corrosive effects of chemical solvents and acid imparted to glass high in MgO content. High-calcium limestone, however, is preferred for the manufacture of non-reusable glass containers.

Product Specifications: The limestone and lime used in glassmaking must be of uniform chemical composition and gradation. High purity is a prerequisite. Generally less than 0.06 percent iron oxide (FeO) is preferred. For glass intended for optical and other special uses, the maximum iron oxide content allowed is 0.01 to 0.02 percent. Sulfur and phosphorous content should be kept to a minimum. Usually, very precise gradation requirements must be met for many operations. For example, 100 percent must pass the No. 10 sieve with 96 to 100 percent being retained on the No. 100 sieve. Many plants cannot tolerate dust finer than the No. 200 sieve or material coarser than the No. 8 sieve. Also, glass manufacturers try to size-match all materials used in their particular system to facilitate more intimate mixing of ingredients.[2]

Paper and Pulp Manufacture

Limestone and lime are used in the paper industry to prepare and/or regenerate cooking liquor for wood pulp digestion. Limestone is employed in the *sulfite process*, where it is reacted with sulfur dioxide (SO_2). This reaction produces a calcium bisulfite cooking liquor which is used to digest wood pulp to separate the cellulose fibers from other constituents in the wood. Lime is employed at one point in the *kraft process* of paper pulp production to regenerate sodium hydroxide (caustic soda) for reuse in the sulfite process.

Most pulp plants use lime for calcium hypochlorite bleaching of paper pulp. Lime sometimes also is used in the chemical treatment and softening of plant process water. For cooking liquor production and regeneration, however, limestone and lime are being replaced by other materials. The replacement of lime is due to environmental problems associated with its use, especially the production of unregenerable sludges which contribute to stream pollution.

Limestone is a weak alkali. It is most effective in neutralizing strong acids to pH levels on the acid side of the pH scale (*under neutralization*). Fine limestone (*limestone flour*) carries the reaction up to a pH of 6.0 to 7.0. A second stage neutralization treatment with lime or other strong alkali is usually necessary to carry the reaction into the alkaline range (*over-neutralization*) to precipitate out ferrous iron and other heavy metals. A two-range neutralization treatment also is used for coal mine process waters and acid drainage, as discussed previously.[21]

Product Specifications: High calcium or dolomitic lime or limestone can be used in the manufacture of paper and pulp. Lime generally is preferred over limestone because of the higher reactivity, although split limestone or lime treatment is employed in some plants. A finely divided lime and limestone is preferred, which is ground to the minus No. 200 sieve or finer.

Flux Stone

Limestone used in the production of steel and non-ferrous metals is referred to as *flux stone*. At one time this application constituted the second largest non-construction use of limestone. The recent decrease in production of American steel combined with improvements in iron ore beneficiation techniques, however, have significantly reduced the limestone tonnage consumed as flux stone. As a result, the total limestone consumption for flux dropped from 22.5 million tons in 1976 to just under 6 million tons in 1987. Limestone use as flux stone now ranks fourth behind cement manufacture, agriculture and lime production.

Steel: Limestone is used as flux in the early stage of steel-making where it is charged into the blast furnace with the raw ore, where it calcines to form lime. The lime, in turn, reacts with impurities to form molten slag that is removed from the system. The impurities the lime reacts with are principally silica, alumina, and lesser amounts of manganese and sulfur. The resulting purified iron is termed *pig* or *cast iron*. The pig iron is either cast into molds and cooled for later use or is recharged in molten form into furnaces downstream from the blast furnace for further refinement into steel.

Impurities in the stone used significantly affect fluxing efficiency. Therefore, the limestone used in the initial ore refining stage must be of the highest purity possible. A stone containing no less than 95 percent total calcium and magnesium carbonate is preferred. Also, the stone should contain no more than about 3 percent total non-carbonate impurities, and less than about 0.1 percent sulfur and 0.02 percent phosphorous.

Other Metals: Limestone also is used as flux for refining copper, lead, zinc and antimony. Limestone flux is charged into the smelters along with the ores bearing these metals in a manner similar to that used in the fluxing of raw iron ore to produce pig iron. The slag produced contains approximately the same type and concentration of impurities formed in the slag produced in steel-making. Limestone specifications are approximately the same as for limestone flux for steel-making. High calcium rather than dolomitic or magnesium stone, however, is preferred for fluxing and refining these metals.[2]

Product Specifications: The type of stone selected frequently is based on the nature of the ore employed and the end use for the resulting slag. For example, if the slag is to be sold as construction aggregates, dolomite or magnesium stone is the preferred fluxing agent. The high magnesium oxide (MgO) content of the slag produced when these limestone are used gives it greater fluidity during the refining process. Upon cooling, high MgO slag tends to produce a harder aggregates. Specifications for portland cement, however, require a finished product low in magnesium oxide. Hence, a high calcium, low magnesium limestone is preferred as the fluxing agent to produce a slag for this purpose.

16.7 Industrial Filler

Uses: The modern world is filled with products made from fine ground limestone products. Known by many names including limestone, calcite, dolomite, marble, marble dust, marble flour, champaign white, calcium carbonate, whiting and Paris white among others, this most useful material will be found hiding in many places in today's homes, factories and automobiles.

About 30 million tons of finely ground calcitic and dolomitic limestone and other calcareous materials valued at over $1.75 billion dollars are consumed annually by American industry as functional fillers or extenders for use in more than a thousand different types of products. Major product groups using fine ground marble and limestone include paint, plastics, paper and rubber products. Specific applications include myriad uses such as paper filling and coating, interior and exterior paint, traffic paint, ceiling paint, PVC pipe, siding and window profiles, plastic film, trash bags, candy wrappers, molded plastic appliance parts, plastic knives, spoons, and forks, plastic and rubber gaskets, joint compound, adhesives, caulks, sealants, and putties, automotive body panels, acoustical sound deadening compounds, cultured marble countertops and sinks, carpet backing, wire and cable jacketing, PVC flooring and many others. In addition, good volumes of ground calcium carbonate are used in applications such as flue gas desulphurization, lime for production of precipitated calcium carbonate, agricultural powders, animal feeds, rice polishing, toothpaste, chewing gum, calcium supplements, medicinal tablet production, mine dusts, oil drilling muds, ceramic and glass production and many others. Even football and baseball fields use ground calcium carbonate for marking the playing area because of its low cost and safety. In fact the paper on which you are reading is probably filled with calcium carbonate.

Many common products found in the home will contain ground limestone or calcium carbonate. Something as common as a pencil eraser tip is made more functional by the use of calcium carbonate. Most erasers of today are actually plasticized PVC and the calcium carbonate helps the eraser remove the pencil marks from the paper by abrading part of itself off rather than not only removing the pencil marks but wearing a hole in the paper as well.

Particle Size: Specifications for calcium carbonate particle size can range from a top size of approximately 20 mesh (840 micrometers) down to products with average particle sizes below one micrometer. Most products in this category of finely ground products commonly will fall 95 percent or more below 200 mesh (75 micrometers) with many exceptions for specific applications. Many of the more functional fillers have low grit levels (325 mesh or 45 micrometers) in order to develop stronger parts. The grit level is said to be the size at which fingers can start to feel individual particles. Table 16.12 illustrates a typical set of particle size distributions for three fine and ultra fine products.

Table 16.12 Particle Size Distribution by Weight of Some Typical Calcium Carbonate Products

Particle Diameter (Microns)	Product		
	A	B	C
44	100	—	—
40	94	100	—
30	84	99	—
20	66	92	100
15	54	81	97
7.5	28	48	85
4	14	26	59
2	7	13	36
1	4	6	20

Product Specifications: Limestone products inherit the characteristics of their parent stone. Specifications regarding color and chemistry are therefore largely determined by that parent stone. Most products used as industrial fillers must be of high purity containing 88 percent or more of calcium carbonate. They should be relatively free of impurities and be of good color. However, not all applications require color properties and there is no nationally accepted color standard for limestone. Many specifications are developed around a specific application's need for certain fitness for use criteria.

Although specifications will vary, the following physical and chemical properties can serve as a guide to selecting an acceptable ground calcium carbonate product for a specific application.

- Good color properties (high brightness/reflectivity) unless the application is non-color critical;
- Low grit levels for fine and ultra fine products;
- Low oil absorption properties;
- High purity, typically 96 percent carbonate although lower purities are acceptable for many applications;
- Low iron levels;
- Meet particle size specifications;
- Low moisture levels; and
- Meet specific customer specifications for agreed upon properties.

Production: Ground calcium carbonate is mined, either by quarrying or via underground mining. Ore from the mine is crushed and then can be further reduced by five basic methods:

- Hammer milling and screening: This will produce products that have been sifted through various sized screens to control particle size.
- Roller milling: This air swept mill uses large steel rolls to crush the ore and often is used in conjunction with some type of an air classifier to develop the desired particle size distribution.
- Tube or ball milling: This uses hard media in a rotating tube mill to crush the ore to fine particles. This type of mill also is used in conjunction with an air classifier to develop the desired particle size distribution. This type of system will develop finer products than a typical roller mill system.
- Low solids water grinding: This type of milling is done at low solids (approximately 30 percent) and can be done autogenously or with grinding media. The material is centrifugally separated into the desired particle size, then filtered, dried and pulverized to a dry powder. This process makes fine and ultra fine products.
- High solids water grinding: This type of milling is similar to low solids grinding but starts out at 75 percent solids and does not require filtering prior to drying. This process makes fine and ultra fine products.

Ground limestone and marble products are sold in 50-pound bags as well as in 2000-3000-pound supersack/tote bags. Dry powdered carbonate also is available in bulk quantities shipped in specialized truck and rail cars equipped for pneumatic conveying. Coarser products can be shipped in bottom dumped covered hopper cars.

Some fine and ultra fine products are surface treated with an organic coating to aid in the wet out of the carbonate into certain organic binders and to develop better physical properties in plastic and rubber applications. Fine and ultra fine calcium carbonate also is available as high solids liquid slurry, widely used in the paper industry.

Everywhere you look you will see products containing ground calcium carbonate but you will have a hard time actually seeing the carbonate. It is truly the "hidden mineral" of today's modern world.

6.8 Miscellaneous Uses

Coal Mine Dusting

One of the greatest hazards associated with coal mine operation is the risk of a violent explosion caused by highly combustible coal dust. The U.S. Congress addressed this problem with the enactment in 1969 of the Federal Coal Mine and Safety Act (Public Law 91-173). The provisions of the act mandate the use of non-combustible mineral dust as a means to prevent explosions. Limestone dust is added to the air and, since it is non-combustible, the highly combustible coal dust is diluted, reducing the risk of an explosion.

Product Specifications: Product requirements specified in the Federal Coal Mine and Safety Act apply today. They have been incorporated in ASTM Designation C 737, Standard Specification for Limestone for Dusting of Coal Mines.[2] ASTM C 737 also specifies that *"either high calcium or dolomitic limestone may be furnished for this application."* The type of stone is not stipulated in the federal regulations.[34]

The properties of mineral dusts used to reduce the risk of an explosion are specified by Public Law 91-173 as follows:

- Fineness: Product shall be ground so that 100 percent passes a No. 20 sieve and 70 percent a No. 200 sieve;
- Silica content not exceeding 4 percent. A low silica content is specified to reduce the risk of silicosis in miners, which is a chronic lung disease;
- Maximum permitted combustibles are 5 percent; and
- A light colored dust shall be used that when wetted does not cake on drying.

Dusting of metallic mines was mandated by Congress for the first time in 1978. Limestone has the majority of this market since it meets the above requirements more easily and economically than do other minerals.[1]

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Chapter 17
Specifications, Standards and Guidelines for Aggregates Base Course

First Edition
Frank P. Nichols, Jr.

17.1 Introduction

Scope

The most widely used standard specifications for aggregates base are those produced by the American Society for Testing and Materials (ASTM), the American Association of State Highway and Transportation Officials (AASHTO), the U.S. Army Corps of Engineers and the individual state transportation agencies. Revisions are made to standard specifications as new performance information becomes available. Therefore, only current specifications should be used for design purposes.

Model specifications for aggregates base and construction recommended by the aggregates industry are presented to promote the most effective use of aggregates with and without artificial binding agents. Finally, recommended practices also are described for construction of serviceable and economical pavements with emphasis being placed on unbound aggregates base and subbase layers.

Specifications

Specifications are designed to define, in measurable terms, the significant characteristics of a material, such as aggregates, desired by a purchasing agency. Specifications comprise all directions, provisions and requirements included in contract documents, either specifically or by reference to available published standards. The purposes of specifications are to:

- Define the quality of materials and construction required to achieve the desired service life.
- Guide contractors in the submission of realistic bids.
- Guide inspectors in the assurance of compliance with quality requirements.
- Describe or make reference to readily available published descriptions of test methods to be employed in judging compliance.
- Form a legal agreement between the owner and the contractor and as such to become an integral part of a contract.

Several types of specifications are used, with varying degrees of success, to specify aggregates and pavement construction:

- **Methods or "Recipe" Specifications:** This type of specification, now seldom used, dictates specific procedures to be followed and materials to be employed. In general, this method is unfair to the contractor since he is both required to meet certain standards while at the same time told what methods must be used.

- **Proprietary Product Specifications:** This type of specification designates contract items in terms of a source or manufacturer and is seldom applicable to aggregates. Occasional exceptions are made when only one source of aggregates is available within a reasonable haul distance.

- **Performance Specifications:** Performance specifications are applicable to work warranted to provide acceptable service for a specific period of one or more years. This type specification is seldom applied to aggregates unless as a special contract provision.

- **End Result Specifications-Statistically Based:** End result specifications are very commonly employed with respect to aggregates base or aggregates as a major component of other products on larger highway contracts. In principle, end result specifications require random sampling of the material in "lots" of designated size, with acceptance decisions made upon average results of a specified number of samples. ASTM Standard Specification D 2940 for graded aggregates base and subbase follows this concept. Acceptance decisions are based upon average results from at least three random samples per unit. A *lot* is defined as approximately 3,000 tons of material. To evaluate gradation, each sample is tested separately. Average values must comply with a job mix formula established before construction is begun, as discussed in the next section. Sampling should be random and follow ASTM Standard Practice D 3665 for Random Sampling of Construction Materials.

The material requirements specified ideally must be measurable by relevant and reproducible test methods believed to be related to the desired level of performance.

> *Under the end result specification concept, failure to conform to end product specification requirements involves reduced payment to the contractor established relative to assumed decreasing serviceability. For example, the pay basis for a given contract item may be cut to 90, 75 or even 50 percent, depending on the magnitude of deviation from specification requirements.*

Typical requirements for aggregate base material and the constructed base, where statistically based specifications are applied, include in-place density, thickness, gradation (with special emphasis on the fraction passing the No. 200 sieve) and Atterberg limits. The burden of providing the required aggregates quality usually is placed on the contractor, who typically shifts this burden to the aggregates supplier and makes a claim for the full penalty against the supplier of aggregates. As insurance against such claims, aggregates producers maintain effective quality control programs, which are discussed in Chapter 18, to produce materials that conform to the specification requirements as delivered and to document this quality in a legally defensible manner.

17.2 Commonly Specified Aggregates Properties

Gradation

The most commonly specified aggregates property is particle size distribution, most often referred to as gradation or grading. Aggregates *gradation* is expressed as a percent by weight of the total quantity of aggregates tested passing a series of standard sieve sizes. While aggregates gradation is usually carefully controlled during processing at the aggregates plant, gradation cannot be readily changed from day to day. As a result, standard aggregates sizes, frequently referred to in specifications, have been developed by ASTM as Standard Practice D 448 and by AASHTO as Standard Specification M-43. Table 11.1, presented in Chapter 11, defines the 10 primary standard aggregates sizes and nine additional intermediate sizes included in these two standards.

The aggregates sizes given in Table 11.1 are not necessarily final end products. Two or more sizes are frequently blended together, with or without the addition of fine aggregates, to produce a final product such as portland cement concrete, asphalt concrete or aggregates base. Also, not all of these sizes are likely to be in stock on demand at a given aggregates plant. Individual aggregates operators usually stock only those sizes most often called for by their customers.

Gradation for Base: Gradation requirements for bases should provide aggregates that resists both permanent and recoverable (resilient) deformation from repeated load applications. Generally mass stability (i.e., resistance to permanent and resilient deformation) is greatest when the particles are densely graded. Dense graded aggregates have a wide range of particle sizes from the top size down to and including stone, dust or filler. This type of gradation fills the void spaces between larger particles with successively smaller particles, thus reducing the total voids in the compacted mass to a minimum.

Dense Grading: The Talbot equation (see Chapter 11, Section 11.3) can be used to obtain a dense aggregate grading which demonstrates good performance and placement characteristics. Use of the exponent n = 0.45 in equation 11-1 (Chapter 11) defines a dense gradation having approximately minimum voids, and hence maximum density for any maximum size of aggregates. When plotted on a special graph whose vertical axis represents percent passing (arithmetically) and whose horizontal axis represents sieve size (to the 0.45 power), the aggregates grading for maximum density appears as a straight line connecting the maximum size (100 percent passing) and the size for which 0 percent passes, as illustrated in Figure 17.1.

Also illustrated in Figure 17.1 are the tolerances for the job mix formula which plot as essentially straight lines as shown by dots in the figure. Note that only the job mix formula must conform to the design or master range. Although the specified tolerances for the job mix formula may allow individual samples outside of this range, the average of all samples representing a lot of material must fall within it. Table 17.1 gives allowable tolerances for job mix formulas.

Guide Specifications: A very useful specification for pavement materials is presented in the next section, with special emphasis placed on the aggregates base. ASTM Specification D 2940 was modeled from this specification and includes the job mix formula concept for control of variability, as illustrated in Figure 17.1. Other standard specifications occasionally applied to aggregates base and subbase materials include AASHTO Standard M-147 and its counterpart ASTM D 1241. These specifications, however, place no control over gradation variability and permit far too many fines (silts, silty clays or clays passing the No. 200 sieve) for the climate and heavy traffic loadings encountered at many locations.

Job Mix Tolerance: Grading specifications, such as given in Table 17.1 require an aggregates base or subbase to fall within a wide grading band. The occurrence of this wide range of grading on a particular job would result in problems in the control of density and moisture content, and might lead to segregation. The job mix tolerance concept is more logical and minimizes these problems by centering the variation in grading about the average gradation for the material used. Job mix tolerance requires, in practice, selecting a particular aggregates source having a known average aggregate gradation. The aggregates delivered to the site must then fall within the job mix tolerance as applied to the average gradation of the selected aggregates.

Recommended job mix tolerances are given in Table 17.1. The aggregates for a base course, for example, passing the No. 4 sieve can vary by ±8 percent from the average. The allowable grading band for that sieve size varies from 35 to 55 percent passing, which is a 20 percent change that would not necessarily be centered about the proposed gradation. *Although aggregates sources can be changed, the same job mix formula should be followed unless caution is exercised in establishing new compaction density, optimum water content and suitable construction practices.*

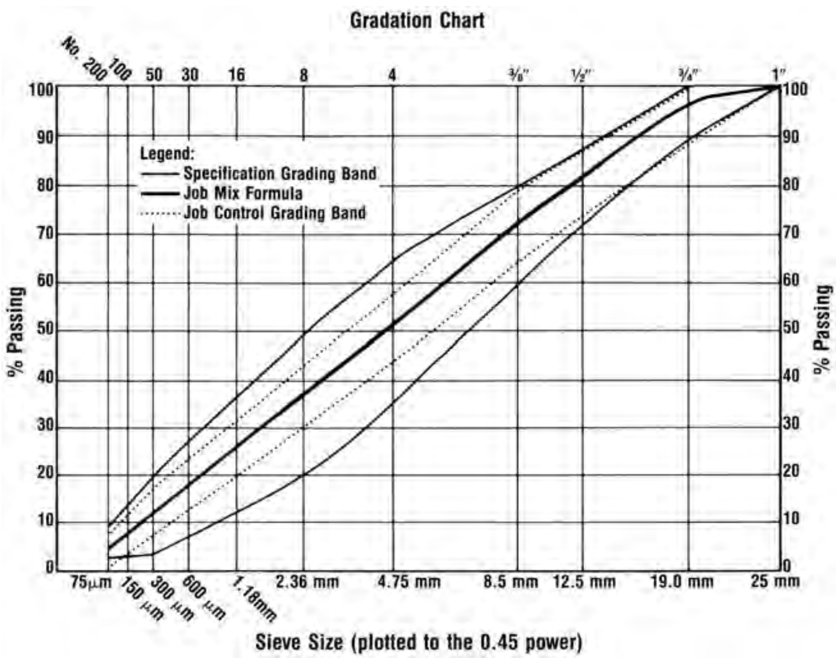

Figure 17.1 Typical gradation chart showing specification and control grading bands.[11]

Table 17.1 Grading Requirements for Dense Graded Aggregates Material.[1]

	Design Range Percentages Passing		Job Mix Tolerances Percentages Passing	
Sieve Size (Square Openings)	**Bases**	**Subbases**	**Bases**	**Subbases**
2 in. (50 mm)	100	100	-2	-3
1 ½ in. (37.5 mm)	95-100	90-100	±5	±5
3/4 in. (19.0 mm)	70-89	-	±8	-
3/8 in. (9.5 mm)	50-70	-	±8	-
No. 4 (4.75 mm)	35-55	30-60	±8	±10
No. 30 (600 µ)	12-25	-	±5	-
No. 200 (75 µ)	0-8	0-12	±3	±5

a. *Job mix formula should be selected with due regard to availability of materials in the area of the project. Job mix tolerances may permit acceptance of test results outside the design range.*

b. *Determine by wet sieving. Where climatic conditions (temperature and availability of free moisture) indicate that in order to prevent damage by frost action a lower percentage passing the No. 200 sieve than permitted above, appropriate lower percentages should be specified.*

Notes:

1. *ASTM Specification D 2940 corresponds closely to this NCSA developed specification.*
2. *Local highway department specifications may be substituted for the design range in the above table, but the appropriate job mix tolerances and limits on the fraction finer than No. 200 should be maintained.*

Wet Sieving: To obtain an accurate indication of the gradation of an aggregates base, the percent passing the No. 200 sieve must be determined by wet sieving, as described in ASTM Standard Test Method C 117. The guide specifications given in both Section 17.3 and ASTM Specification D 2940 require wet sieving. ASTM Method C 136, which is adequate for sieve analysis of aggregates and aggregates mixtures containing little or no clay-like fines, cannot be used alone for accurate determination of the percent finer than the No. 200 sieve. Test methods for determining gradation are described in more detail in Chapter 3.

Inherent Aggregates Quality

Most specifications attempt to define the level of aggregates quality needed for given service applications. Typically they include very general requirements, such as the particles should be reasonably clean, i.e., free from adherent coatings of clay, silt, etc., and be hard, strong, durable, sound, well-shaped, etc. Quality also may be defined in terms of many of the basic physical, chemical, and mechanical properties described in Chapter 3 and also Section 17.3 of this chapter. Unlike gradation, most qualities are inherent in the mineral deposit and cannot be altered appreciably by processing. Unfortunately, attempts to measure many of these properties quantitatively, particularly hardness, durability, soundness or weatherability and toughness, and to correlate the measurements with performance in particular applications, continue to fall short of the goal. Quality specifications therefore are still based on essentially empirical test methods. Many of these test methods are used for lack of more precise fundamental testing techniques. The most widely used test methods are described in Chapter 3.

Aggregates specifications, either for gradation or for quality, should be tailored to the importance of the work-thus they should be adequately restrictive on more critical construction such as expressway pavements, but not as restrictive on, for example, driveways and parking lots.

Locally Available Materials: Aggregates specifications, including those established by AASHTO, often are written around material sources most readily available. The reason for this is that aggregates cost at its point of use is very often governed more by the cost of transportation than by production cost as the following AASHTO's policy specifies:[2]

> *"Test limits considered the most liberal that may safely be allowed ... with the understanding that where higher grade materials are locally available, more rigid requirements should be inserted."*

Table 17.2 tabulates both the mandatory and supplementary requirements of AASHTO Standard Specification M-283. AASHTO Standard Specification M-283 covers coarse aggregates for use in macadam-type base and surface courses, graded aggregates base courses, asphalt concrete base and surface courses, and bituminous surface treatment. The specification establishes three classes of aggregates: A, B, and C, and requires the user to select and specify the class and gradation (size number) desired. The methods of test referenced for establishing compliance with these requirements include AASHTO Standard Methods T-19 (unit weight of aggregates), T-27 (sieve analysis of fine and coarse aggregates), T-96 (resistance to abrasion of small size coarse aggregates by use of the L.A. machine), and T-104 (soundness of aggregates by the use of sodium sulfate or magnesium sulfate).

Table 17.2 Aggregates Quality Requirements

		Class A Aggregates	Class B Aggregates	Class C Aggregates
Abrasion by Use of L.A. Machine, Percentage of Wear, max[1, 4]		40	45	50
Soundness, Weighted Average, Percent Loss, max	5 Cycles Sodium Sulfate[2]	12	12	12
	5 Cycles Magnesium Sulfate[2]	18	18	18
Density, Kg/m^3 (lb/ft^3), min[3]		1120 (70)	1040 (65)	960 (60)

Notes:

1. *Should not apply to air-cooled blast furnace slag.*
2. *Either solution may be used, as specified.*
3. *Density requirements should apply to slag aggregates only.*
4. *Aggregates with a percentage of wear greater than the maximum values specified above may be used if a previous satisfactory service record can be demonstrated.*

Supplementary Requirements

One or more of the following supplementary requirements may be made a part of this specification only by reference in the contract documents.

S1 Coating and stripping of Bitumen-Aggregates Mixtures, minimum retained coating, 95 percent when tested in accordance with the requirements of AASHTO T-182.

S2 The portion of the total aggregates passing the 0.425 mm (No. 40) sieve should have a plasticity index of not more than six when tested in accordance with the requirements of AASHTO T-90.

S3 Adherent coating on aggregates after first dry sieving on 0.075 mm (No. 200) sieve should not exceed 0.5 percent when tested in accordance with the requirements of AASHTO T-1 1.

S4 Crushed gravel should consist of particles with not less than 75 percent of the portion retained on the 4.75 mm (No. 4) sieve having at least two fractured faces.

S5 Crushed gravel should consist of particles with not less than 50 percent of the portion retained on the 4.75 mm (No. 4) sieve having at least two fractured faces.

S6 The portion of the total aggregates passing the 4.75 mm (No. 4) sieve should have a sand equivalent (S.E.) value of not less than 35 when tested in accordance with the requirements of AASHTO T-176.

S7 The proportion of aggregates retained on the 9.5 mm (⅜ inch) sieve should not contain more than 15 percent of particles by weight so flat or elongated, or both, that the ratio between the maximum and the minimum dimensions of a circumscribing rectangular prism exceeds 5:1.

17.3 Guide Specifications for Pavement Materials and Construction

This section presents guide specifications which, if followed, will ensure the proper construction of aggregates bases, especially for asphalt concrete pavements. These specifications are taken from the publication "Flexible Pavement Design Guide for Roads and Streets."[1] Aggregates as an important component in other types of construction is covered in Chapter 13.

The following suggested specifications are offered to provide assistance in preparing contract documents, but are not designed to be comprehensive.

General Aggregates Grading Concepts

Coarse Aggregates: Aggregates retained on the No. 4 sieve should consist of durable, angular fragments of crushed aggregates obtained from an approved quarry. Three general classes of crushed aggregates quality are defined in Table 17.3.

Table 17.3 Aggregates L.A. Degradation and Soundness Requirements[1]

Class	Percent Loss L.A. Machine, Max*	Percent Loss Soundness, Max**
A	40	12
B	45	15
C	50	18

* *After 500 revolutions (ASTM Method C 131 or C 535). Where local highway specifications permit higher losses or require lower losses, such specifications may be applied.*

** *After five cycles (ASTM Method C 88, Sodium Sulfate Solution). Note: Where magnesium sulfate solution is used, maximum limits may be increased 50 percent. Requirements applicable to areas of severe climate only. In other areas, or where service records indicate, requirements may be modified or waived.*

Fine Aggregates: Fine aggregates passing the No. 4 sieve should consist essentially of particles produced from the crushing of coarse aggregates at the approved source. Other types of fine aggregates, if permitted for limited use, should meet local highway department quality requirements.

Grading: The grading (size number) and class of aggregates to be furnished should be specified from Table 11.1 given in Chapter 11 or from an equivalent table of standard sizes given in local highway specifications. This table duplicates the table given in ASTM Specification D 448 identifying all of the standard aggregates gradations originally developed through the U.S. Bureau of Standards and published as Simplified Practice Recommendation (SPR) 163-48.

Graded Crushed Stone Bases and Subbases

This specification covers materials and construction for quality controlled graded crushed stone bases and subbases for flexible pavements.

Coarse Aggregates: Aggregates retained on the No. 4 sieve should be crushed stone Class C or equivalent, should be produced from an approved quarry, and should be capable of withstanding the effects of handling, spreading and compaction with minimum degradation.

Fine Aggregates: Material passing the No. 4 sieve should consist of particles produced during the crushing of coarse aggregates at the approved source. Its sand equivalent value should be no lower than 30 or its minus No. 40 sieve size fraction should not have a liquid limit greater than 25 or a plasticity index greater than 4.

Composite Mixture—Dense Graded Material: *Grading:* The grading of the final dense graded base or subbase mixture should conform to the requirements of Table 17.1. The job mix formula should be established prior to the beginning of the work, and should not be changed during the progress of the work without the approval of the engineer or his authorized representative.

CBR Value: The laboratory compacted CBR value (ASTM D 1883) of the materials to be used as the base should not be less than 100 after curing and four days soaking. Test specimens should be compacted at optimum moisture by the "modified" method (ASTM D 1557, Method D).

Composite Mixture—Open-Graded Drainage: *Grading:* The grading of the final open-graded base or subbase mixture should conform to the requirements of Table 17.4.

Table 17.4 Grading Requirements for Open-Graded Drainage Layer Material[1]

Sieve Sizes (Square Openings)	Design Range Percent Passing	Tolerance
1 ½ in.	100	0
3/4 in.	70-95	±5
3/8 in.	35-65	±8
No. 4	20-40	±8
No. 16	0-10	±4
No. 50	0-5	±2
No. 100	0-3	±1

Construction: Crushed stone base (or subbase) layers should be constructed in accordance with the applicable sections of the local highway department specification for base material. NOTE: Valuable tips on construction may be obtained from NSA's "Stone Base Construction Handbook."[10]

Placing: Crushed stone base material should be placed in layers of uniform thickness with an approved spreader. Layer thicknesses generally should not exceed 6 inches after compaction. Dense graded base material (Table 17.1) should be delivered to the spreader at its optimum moisture content (±1.5 percentage points) as determined by ASTM D 1557 (AASHTO T-180).

Open-graded drainage layer material (Table 17.4) should be placed in lifts not to exceed 5 inches. Track type spreaders are recommended for spreading subsequent layers.

Compaction: Dense-graded stone base should be compacted while at its optimum moisture (± 1½ percentage points), using equipment capable of obtaining the desired density to the full depth of the lift. Continuous passes of the compaction equipment should be made until the material reaches a density not less than 100 percent of the maximum laboratory density as determined by ASTM D 1557, Method D (AASHTO T-180). In-place density should be measured by ASTM Method D 2167 or other approved methods.

Open-graded drainage layer material should be compacted by pneumatic-tired or vibratory rollers until little or no significant movement is observed in the separate particles, which should be locked into place. Construction or other traffic should not be allowed on these open-graded layers; the choke course of more densely graded material or the first layer of hot mixed asphalt should be placed promptly on open-graded drainage layers, before any traffic is permitted.

Finishing: The surface of the completed crushed stone base should be finished by blading or by means of automated equipment to produce a final surface having no deviations in excess of 0.5 inch when tested with a 10-foot straight edge. The completed thickness of the base should be measured at frequent intervals as defined in the contract documents; the average thickness should be not less than the design thickness, and individual measurements should be within +.75 inch or -0.5 inch of the thickness indicated.

Sampling Practices and Methods of Testing: Materials should be sampled and properties enumerated in these specifications should be determined in accordance with the practices and test methods described in Chapter 16. Further details on sampling of dense graded base materials may be found in ASTM Specification D 2940.[13]

Hot Mixed, Hot Laid Asphalt Surfacing

This specification covers quality controlled hot mixed, hot laid asphalt paving mixtures for binder and surface courses.

Coarse Aggregates: Aggregates retained on the No. 8 sieve should be crushed stone Class A or equivalent. The aggregates should be produced from an approved quarry, and should be capable of withstanding the effects of handling, mixing, spreading and compaction with minimum degradation.

Fine Aggregates: Material passing the No. 8 sieve should consist essentially of particles from the operation of crushing the coarse aggregates from an approved quarry. Other mineral aggregates may be added if necessary as an aid to workability, up to a maximum of 25 percent, provided that local experience has demonstrated their ability to produce satisfactory asphalt paving mixtures. The final blend of fine aggregates should meet the quality requirements found in ASTM Specification D 1073.

Mineral Filler: When the composite coarse and fine aggregates is deficient in material passing the No. 200 sieve, mineral filler conforming to ASTM Specification D 242 may be added.

Asphalt Material: The asphalt material should be asphalt cement of an appropriate grade conforming to ASTM Specification D 946 or D 3381 (AASHTO M-20 or M-226).

Composition of Mixture: The grading of the aggregates, coarse and fine, with the added mineral filler (if needed) should be such that they can be blended together to produce a mixture conforming to an appropriate final-grading band and uniformity tolerances, as defined in ASTM Specification D 3515. The asphalt content should be that needed to produce a laboratory-compacted mixture meeting the stability, voids and other criteria defined in the contract documents.

The Marshall (ASTM D 1559), Hveem (ASTM D 1560), or other appropriate method should be used to determine compliance with such criteria.

Spreading and Compaction: Hot mixed asphalt concrete should be spread and compacted with approved equipment at the temperatures and weather limitations established by local highway department specifications. Compaction equipment should be operated as close behind the spreader as possible to attain at least 98 percent of the laboratory design density for the specific mixture. The finished surface should be smooth and, when checked with a 10-foot straight edge, should show no deviations greater than 0.25 inch.

Sampling Practices and Methods of Testing: Materials should be sampled and properties enumerated in these specifications should be determined in accordance with the practices and test methods presented in Chapter 16.

Asphalt Surface Treatment

This specification covers the materials and construction of single or multiple course asphalt surface treatments.

Aggregates: Cover aggregates should be crushed stone Class A, or equivalent, should be produced from an approved quarry, and should be capable of withstanding the effects of handling, spreading and compacting with a minimum of degradation. Cover aggregates should meet the quality requirements of ASTM Specification D 1139 and the grading requirements of the appropriate simplified practice (SPR) size suggested in the Appendix to D 1139 (see Table 11.1).

Asphalt Materials: All asphalt materials should conform to requirements set by the local highway department or should be appropriate grades of cutback or emulsified asphalt meeting the requirements of ASTM Specifications D 2028 (Liquid Asphalts) or D 977 or D 2397 (Emulsified Asphalts). For maintenance seal coating, a softer asphalt cement meeting the requirements of ASTM D 946 (150-200 or 200-300 penetration) may be used where it has been shown to provide satisfactory service.

Construction: The existing roadway should be inspected and any soft or yielding areas removed, replaced with a new crushed stone base and properly compacted. The balance of the operations should be in accordance with local highway department specifications, including equipment used and weather limitations, unless otherwise directed by the engineer.

Sampling Practices and Methods of Testing: Materials should be sampled and properties enumerated in these specifications should be determined in accordance with the practices and test methods presented in Chapter 16.

Penetration Macadam Pavements

This specification covers materials and construction methods for penetration macadam bases or pavements. A penetration macadam base consists of one or more courses of large size, coarse aggregates, at least one application of asphalt cement or asphalt emulsion, and at least one application of a small sized, coarse aggregates to lock the larger aggregates particles in place.

Aggregates: All aggregates should be crushed stone Grade B or equivalent, should be produced from an approved quarry and should be capable of withstanding the effects of handling, spreading and compacting with a minimum of degradation. The coarse aggregates should meet the gradation requirements of SPR size 3 or 4, the key or choke stone the requirements of SPR size 6 or 7, and the final cover stone requirements of SPR 7 or 8 (see Table 11.1), or the most closely corresponding local highway department specification sizes.

Asphalt materials: All asphalt materials should conform to the requirements of the appropriate local highway department specifications or should be an appropriate grade of material meeting the requirements of ASTM Specification D 946 (Asphalt Cement), D 2027 (Medium Curing Cutback Asphalt), or D 977 or D 2397 (Medium Setting Emulsified Asphalt).

Construction: The crushed stone base should be compacted and finished as required and swept clean. Coarse aggregates should be spread uniformly for a full lane width by means of approved mechanical spreaders. The aggregates should be dry rolled until the particles are well keyed together and the surface will support the distributor without distortion. Dry rolling should be stopped before the voids are closed sufficiently to prevent free penetration of the asphalt material. Asphalt materials should next be applied by means of an approved distributor in good working order. Immediately afterward, key or choke aggregates should be spread and worked into the voids by rolling and broom dragging until the course is uniformly filled and compacted. Upon completion of this application, a second application of asphalt material should be made, the final cover aggregates applied and the surface rolled and broomed to a uniform texture.

Sampling Practices and Methods of Testing: Materials should be sampled and properties enumerated in these specifications should be determined in accordance with methods described in Chapter 16.

Sampling Practices and Test Methods

Materials should be sampled and the properties enumerated in these specifications determined by the following methods of ASTM or AASHTO.

Table 17.5 ASTM and AASHTO methods

	ASTM	AASHTO
Practices to be Followed		
Sampling aggregates	D 75	T-2
Sampling bituminous materials	D 140	T-40
Sampling bituminous paving materials	D 979	T-168
Characteristics to be measured		
Sieve analysis, aggregates	C 136	T-26
Material finer than No. 200, aggregates	C 117	T-11
Plastic fines in aggregates and soils, sand equivalent	D 2419	T-176
Liquid limit, minus No. 40 fraction	D 4318	T-89
Plastic limit and PI, minus N. 40 fraction	D 4318	T-90
Moisture-density relation	D 1557	T-180
Bearing ratio (CBR), four day soak)	D 1883	T-193
Density in-place, after compaction	D 2167	T-205
Plastic Flow, Marshall Test, bituminous mixtures	D 1559	T-245
Deformation and cohesion, Hveem Test, bituminous mixtures	D 1560	T-246

17.4 Aggregates for Base Courses

Functions of a Base Course

Flexible Pavements: Base courses for flexible pavements should provide the aggregates interlock and interparticle friction essential for stability under applied wheel loads. Normally, a dense grading is preferred with the material containing enough fines (4 to 8 percent) to hold its shape during compaction and the construction of overlying layers. The voids in the aggregates should not, however, be overfilled with fines so as to completely block drainage, resulting in reduced strength, and create other problems. An unbound aggregates base or subbase should be compacted to its maximum practicable density to minimize permanent deformation from applied loads.

Rigid Pavements: One main function of the base or subbase course under portland cement concrete rigid slab pavements is to provide uniform support, especially at the slab joints. The base or subbase also should prevent pumping as heavy wheel loads pass across these joints. Pumping expels any free water trapped under the slab. This movement of water often erodes fine soil particles from the underlying layer, resulting in the creation of void spaces beneath the joints and premature pavement distress in the form of faulting and spalling of the surface. Aggregates for this use should have a reasonably open gradation with few if any fines. The coarser side of the grading specifications given in Table 17.5 can be used beneath rigid pavements. In some areas the practice is to stabilize a very open graded material with a low percentage of asphalt or cement.

Compacting Base Material

Thick Lift Bases: New compaction equipment and recent research have demonstrated that graded aggregates base can be successfully compacted in lifts up 21 inches in depth.[14] Densities up to 100 percent of AASHTO T-180 are readily achieved when well-graded aggregates are compacted at optimum moisture. Moisture content is best controlled when the aggregate is processed through a pugmill. Acceptable densities can be achieved with a 7-ton or larger vibratory compactor with dynamic loads of 45,000 to 55,000 pounds.[14] The number of passes required is a function of the size, shape and grading of the aggregates used and the size of the compacting equipment.

Pad Foot Compactor: Recent research has demonstrated that a pad foot vibratory compactor is extremely effective during the first two passes for thick layers of aggregates base. Aggregates degradation does not occur in deep lifts if the aggregates is at optimum moisture and the base is not subjected to more than two passes of the pad foot vibratory compactor. Subsequent compaction should be accomplished with a combination of standard vibratory and pneumatic compactors.[14]

Test Sections: Rolling patterns are determined best from field test sections. Gradation control and optimum moisture are both important considerations in achieving maximum density. The use of test sections to establish target compaction densities is discussed below.

Importance of Compaction

A well-graded base course conforming to the specifications given in Section 17.3 should provide the necessary support for either flexible or rigid pavements. A key word for obtaining good performance is *compaction*, which must be neither overlooked nor neglected. Even the best aggregates mixture must be thoroughly compacted for its potential load bearing capacity to be fully mobilized.

Laboratory Tests for Determination of Maximum Density

> *"The determination of the unit weight of soil or graded aggregates in a standard condition of compaction is an essential element of construction control specifications."*[6]

A standard condition of compaction can be established either by laboratory testing or in the field by a compaction control strip as described in this section.

Compaction Tests: Either the *standard Proctor* (AASHTO T-99) or the *modified Proctor* (AASHTO T-180) density tests are used in the laboratory to establish a standard reference density. These tests originally were developed for embankment soils. The standard and modified Proctor tests are designed to produce a well-defined, moisture-density relationship (curve) that gives an optimum moisture content corresponding to the maximum dry density obtained using a specific compactive effort. The compactive effort is defined as a specific number of impacts from a standard hammer of a specific size and weight prescribed by the test method being used (refer to Chapter 3).

Moisture-Density Relations: Figure 17.2 illustrates the moisture-density curve obtained from laboratory testing for an aggregates base material. The *maximum dry density* obtained from the test corresponds to the peak of the moisture-density curve and is about 141 pcf. The *optimum moisture content* is the moisture content associated with the maximum dry density and is about 5.7 percent.

The terms *optimum moisture* and *maximum dry* density are not fundamental properties, but vary with respect to the specific compactive effort used and method of compaction even for the same material. Many granular materials do not produce the well-defined "peak" shown in Figure 17.2 since the moisture tends to drain rapidly to the bottom of the mold before the test specimen can be weighed and its moisture content determined.

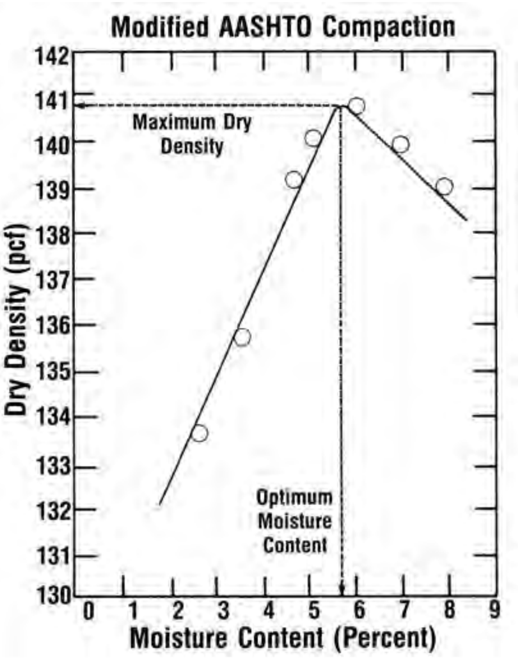

Figure 17.2 Relation between moisture content and dry density.[11]

Vibration: Another laboratory test method occasionally used to establish a reference density involves vibration of the material. The vibration test can be performed on dry aggregates but more often the test is performed on aggregates that is in a practically saturated condition. ASTM Test Method D 4253 produces a maximum index density through use of a vertically vibrating table. Research performed by the National Crushed Stone Association[3] has found that a combination of tamping and vibration is highly effective in preparing specimens of crushed stone base material for triaxial testing.

Target Density: One objective of laboratory density testing is to determine a unit weight of dry solids in the compacted condition that can be related to a dry density of the same material properly compacted in the field. This target density can be more or less than 100 percent of the maximum density obtained by the specific laboratory procedure. *In specifying the proper percent of the reference density, it is essential that the precise method of test used to establish the reference density is clearly stated.* For example one might specify 100 percent of AASHTO T-180 maximum dry density. Merely specifying 100 percent maximum dry density is not adequate since a precise test method is not specified.

Oversize Particles: Most laboratory density test methods are limited in their ability to establish a true maximum density for coarser base materials since the apparatus cannot accommodate particles larger than about ¾ inch maximum size. In some testing procedures, all the ¾-inch aggregates is scalped from the sample. Some of the procedures permit replacement of the +¾-inch material with finer material in the ¾ inch to No. 4 mesh range. However, whether the +¾-inch material is replaced or not, the sample is no longer truly representative of the material proposed for construction. For accurate representation of the base, all material sizes should be included.

Illustrative Example: A more mathematically correct method[7] employs a nomograph solution to compensate the test result for the presence of oversize material. This nomograph is presented in Figure 17.3. In the example shown on the nomograph, a laboratory dry density of 141 pcf has been determined on the minus ¾ inch fraction by AASHTO Method T-180. To solve for the maximum dry density corrected for 30 percent oversize particles, enter the 141 pcf density on the left axis of the nomograph (Point 1). Enter the bulk specific gravity (2.68) of the oversize aggregates on the right side (Point 2). The bulk specific gravity should be determined using AASHTO Method T-85 or ASTM C 127. Now determine the location where a line connecting Points 1 and 2 intersect the line for 30 percent oversize particles establishing Point 3. Then move from Point 3 horizontally to the left across the nomograph establishing Point 4 which is the desired maximum dry density (148 pcf) corrected for oversize particles. When more than about 30 percent oversize is present, the nomograph method of correction given in Figure 17.3 becomes less accurate.[7]

Field Control Strip Method for Determining Maximum Density

The problem associated with establishing a reference density in the laboratory when oversize material is present can be avoided by using a section of the aggregates base or subbase placed in the field as a *control strip*. A *control strip* is constructed at the beginning of work on each lift of the base or subbase. The control strip is compacted, using equipment and methods known to be effective, until no appreciable increase in density is attained through repeated coverages by the compactor. A number of random tests are then made to determine the average dry density of the test strip. This density becomes the reference density against which succeeding sections of that lift are compared. Nuclear test methods commonly are used for more rapid measurement of the moisture and density in the control strip after successive passes of the compactor.

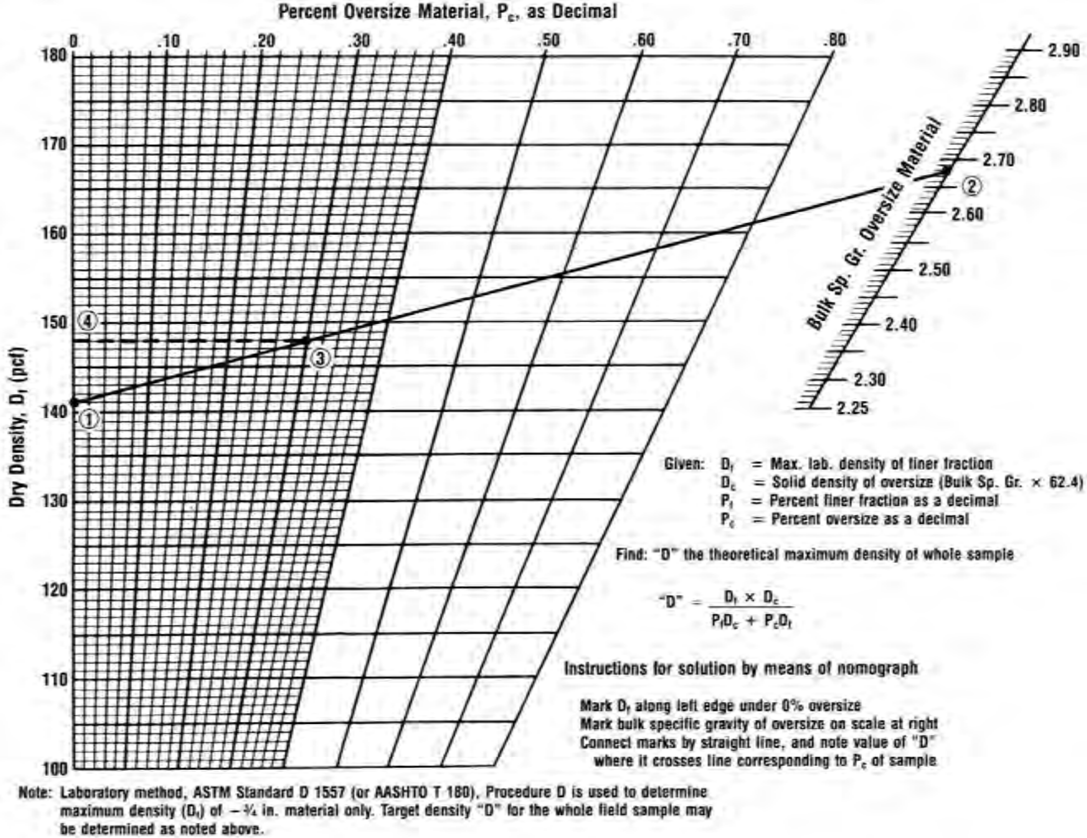

Figure 17.3 Nomograph for determining correction for oversize material in field test sample (+3/4 in.): reference Virginia DOT method V.T.M.1.

Statistical Density Control: Compaction specifications used by the Department of Transportation Virginia require dividing the area to be tested into lots (i.e., partitions). Random samples are then taken in the lots and the average density achieved must be at least 98 percent of the control strip density. Further, only one out of five tests should be less than the specified control strip density but not greater than 2 percent less than the control strip density. Since density control is based on the results of the test strip, care should be exercised to maintain the same aggregates grading throughout the project so that density control is correct. More densely graded aggregates has enough fines to completely fill the voids between the coarser particles resulting in a higher density than more open graded aggregates. Problems may also occur if the subgrade support at the control strip site is more or less than that found elsewhere along the project.

Effect of Gradation and Density on Drainability

Aggregates base layers are often expected to perform two separate and contrasting functions:

- Provide stability through aggregates interlock and particle friction;
- Provide adequate drainage of water that enters the pavement structure. This water, if allowed to remain within the bases, significantly shortens the life of the pavement.

Figure 17.4 shows that the maximum shear strength and density of aggregates base is developed when the material is dense graded and has about 8 to 9 percent fines. Figure 17.5 indicates schematically the difficulty aggregates base has in providing stability while at the same time being permeable enough to permit rapid drainage of water from the base. Figure 17.6 shows relationships between percent fines and permeability (expressed as the coefficient of permeability k) and stability, as measured by the CBR test.[6] These and other experimental findings show that:

- Permeability decreases with increasing fines; a base is not free draining if more than about 2 percent fines are present.
- An increase in fines increases stability until an optimum level is reached. Increases above that level result in decreased stability.

A complete discussion of the effect of aggregates properties on shear strength is given in Chapter 11 while the effects of aggregates gradation on permeability are considered in Chapter 12. In summary, maximum stability usually is developed in a well-graded aggregates containing 6 to 9 percent fines. Maximum density often requires the presence of a few more fines to completely fill the voids, but these additional fines produce greater susceptibility to frost and moisture (see Chapter 11). Good drainability is provided by a much more open-graded aggregates containing few if any fines.

Gradation Philosophy: Two separate philosophies are currently used in pavement design practice in an attempt to maintain stability and improve permeability of aggregates bases:

- One philosophy holds that the gradation must be practically devoid of fines. If necessary to provide stability during construction, aggregates are treated with just enough asphalt or portland cement to provide the stability needed to support construction traffic until it can be confined by the final wearing surface. A base so open-graded that it must be stabilized with asphalt or cement may cost twice as much as one not quite so open. Also, problems with stability have been observed with these very open-graded bases.

- The second philosophy attempts to improve permeability by removing some of the fines while both maintaining the desired stability and also minimizing the increase in the cost of production over more conventional dense graded aggregates.

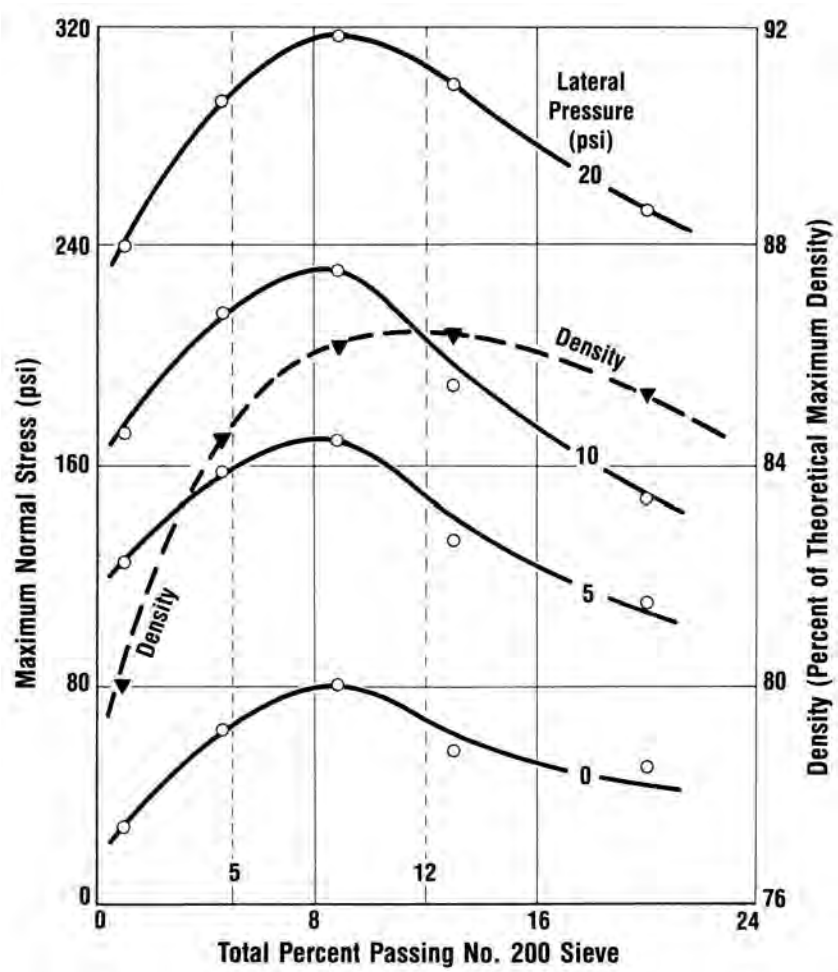

Figure 17.4 Effect of minus No. 200 content upon density (% of solid or theoretical maximum) and triaxial compressive strength.[3]

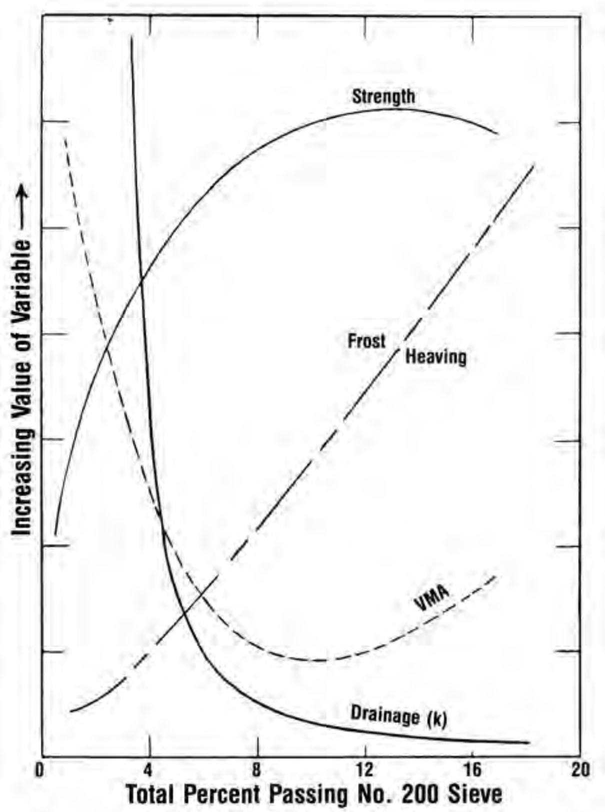

Figure 17.5 Summary of effects of minus No. 200 content on triaxial strength, frost heave potential, density (VMA), and drainability of a 1 ½ in. maximum size limestone.[3]

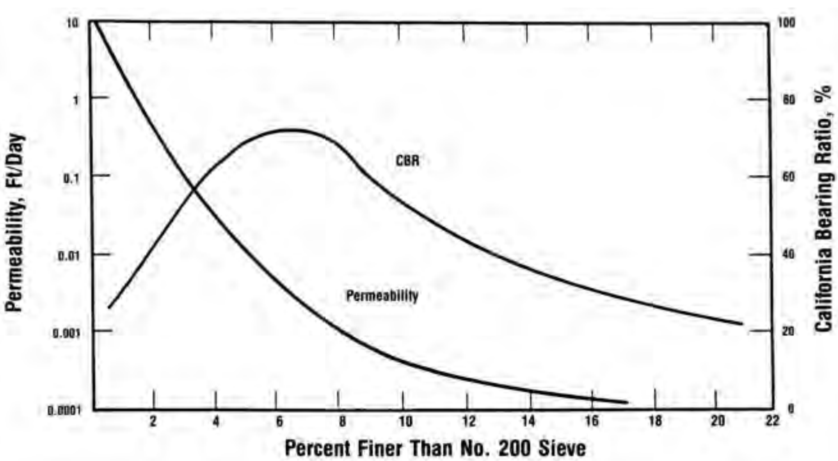

Figure 17.6 Relationship between stability and permeability.[11]

Advantages and Disadvantages: Both design philosophies have advantages and drawbacks. Use of the open-graded base alleviates the problems of frost and moisture susceptibility, but is considerably harder to construct. Use of an open-graded base which requires a cementing agent can create a condition of turbulent flow as water is discharged. This turbulent flow condition tends to erode fines from the underlying subbase or subgrade. On the other hand, a small reduction in the percentage of fines reduces frost and moisture susceptibility somewhat, but provides little if any significant improvement in drainability.

An open-graded layer must be protected by a filter layer to prevent becoming clogged with fines from materials lying below or above that layer. Preferably filter protection should be provided by using a more dense-graded aggregates meeting the filter criteria given in Section 12.3 of Chapter 12.

Recommended Gradation for Drainage of Aggregates Base: A practical compromise between the two design philosophies has been recommended based on research reported by the Departments of Transportation in Pennsylvania[8] and New Jersey.[9] These recommendations for a more free-draining aggregates gradation are presented in Table 17.4 of the model specifications given in Section 17.3. The recommended gradation is most readily produced by blending a standard coarse aggregates size such as No. 57 stone (Table 11.1), and a smaller-sized coarse aggregates or washed stone screenings. Aggregates blend having this grading, when composed entirely of angular crushed material, should provide the required stability under controlled construction traffic without the addition of a stabilizing agent.

Positive Removal of Water from the Base: Provision for positive outlets to remove quickly any water that becomes trapped in the pavement structure is a most important consideration for any type of construction and especially when open-graded base layers are involved. Continuous edge drains are recommended construction practice; these drains consist of perforated pipes embedded in pea-sized aggregates wrapped in a geotextile. Solid pipe lateral outlets are placed at intervals across the shoulder to the slope or ditch. Outlets should be carefully marked and protected from damage during maintenance operations, as shown in Figure 17.7.

Figure 17.7 Outlet from longitudinal pipe drain

17.5 Construction Methods and Control for Aggregates Base

Introduction

A National Stone Association publication, which is a pocket-sized construction handbook,[10] contains valuable tips on aggregates base construction. Emphasis is placed on quality control of the aggregates all the way from the quarry face to the completed, compacted base. Quarry sources should be carefully selected to produce sound rock of good quality and the plant process should be designed to ensure consistent gradation within reasonable tolerances. Also, the finished material should be loaded at the quarry at a suitable moisture content to facilitate compaction.

Subgrade

Of extreme importance is the provision of a firm, well-drained subgrade, as uniform in character as possible. Areas of unsuitable subgrade soils should be corrected before base course construction begins. Unsuitable subgrade soils include those characterized as poor on the basis of CBR tests on samples obtained during a preliminary soil survey, and also include localized pockets high in organic matter or too wet to be compacted properly. The CBR test is described in Chapter 3.

Soil support categories are defined as follows:[1]

CBR	Support Category
15 +	Excellent
10-14	Good
6-9	Fair
5 or less	Poor

Stabilization: Another very effective method for evaluating the subgrade is to proofroll it using a heavy piece of equipment such as a loaded dump truck. Proofrolling preferably should be carried out in both directions. Areas which deform excessively or roll should be undercut and replaced with suitable backfill or stabilized using one of the stabilizer stones specified in Table 11.20 in Chapter 11. *The rule of thumb is that as the softness of the subgrade increases, the size of the stabilizer stone used should become larger.* To stabilize extremely soft areas, surge stone should be employed. *Surge stone* is about six inches or larger in diameter and has been processed only through the primary rock crusher.

Preparation: Thorough preparation of the subgrade on which the base course is to be placed should include:

- Good drainage to remove rainwater that might form ponds on the subgrade and create soft spots. This is best accomplished by providing weep holes through the shoulders at low points.
- Thorough compaction of the subgrade with appropriate equipment. In general the upper 12 inches of the subgrade should be compacted to at least 100 percent of AASHTO T-99 maximum dry density. Sheepsfoot rollers usually perform well in cohesive soils such as clays and silts. Vibratory rollers and pneumatic tired rollers can be used in cohesionless soils such as sands.
- Careful inspection is required to assure compliance with job requirements concerning compaction, elevation, slope and crown.

Spreading the Base Material on the Grade

Mechanical Spreaders: The aggregates should be brought to the job at the specified gradation and required moisture content. The aggregates should be placed in layers to a uniform loose depth no greater than eight to ten inches, and compacted to the specified density using a minimum of blading to avoid segregation. Stone compacts to a depth of about two-thirds of the loose thickness. For example, 8 or 9 inches in loose depth are required for a final compacted thickness of 6 inches.

Spreading is most economically accomplished by means of mechanical *stone boxes* such as a Jersey spreader. The Jersey spreader is designed to lay the aggregates full lane width, true to line and grade, to the specified thickness. Mechanical spreaders are preferable to tailgating or dumping in piles which tend to develop segregated spots of all coarse or all fine aggregates. Spreading equipment for base material ranges from highly automated, self-propelled, mechanical types to the simple, tractor-pushed spreader.

End Dumping: Where it is not practical to employ mechanical spreaders, the aggregates should be end dumped on the subgrade and carefully spaced at planned intervals to minimize the distance material must be moved. This procedure minimizes the potential for segregation.

Compacting Aggregates Base

Importance of High Density: Compaction to a high-density level is the best known and most economical method of developing stability in crushed aggregate bases. The great importance of compaction to the structural capacity of a pavement is shown in Figure 17.8.

Equipment Selection: Proper compaction equipment must be chosen and used efficiently. Some types of compactors achieve the necessary compaction with less effort than other methods, often with the aggregates being at a lower moisture content than for other methods.

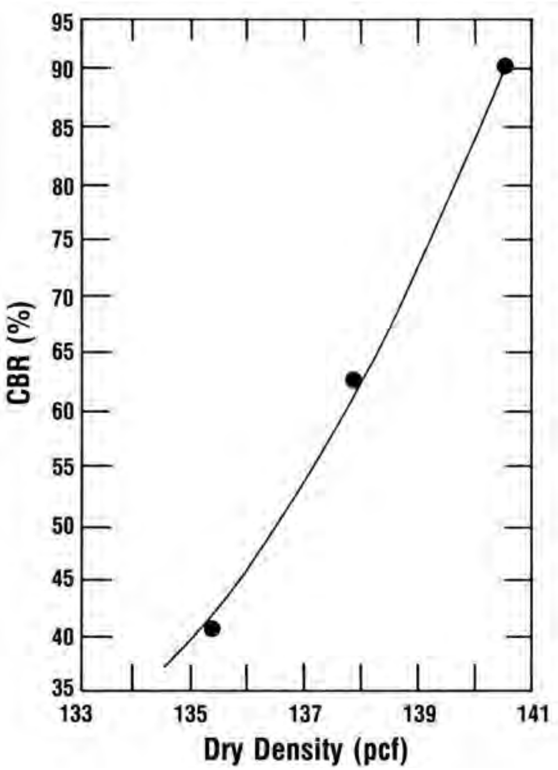

Figure 17.8 Effect of Increased density on CBR value.[11]

The factors to be considered in choosing the best compaction equipment for the job include:
- Types of material to be compacted (in addition to the base);
- Size of the job;
- Time factor—the rate of compaction must be geared to rate of placement; and
- Currently owned or available equipment.

On large jobs the most efficient machine should be selected for compaction of the base, since a few cents saved per cubic yard in operating costs can more than offset a major investment in equipment. The advantages and possible disadvantages of certain types of compaction equipment are as follows:

1. **Vibratory Compaction:** For stone base construction, probably the most efficient and most versatile machine available is the self-propelled vibratory roller. These units are relatively light and easily moved between jobs. Vibratory rollers are available in both towed and self-propelled models in a wide range of sizes and weights; machines with vibration frequencies from about 800 to about 4,000 blows per minute have been manufactured. The most popular models are self-propelled vibratory rollers with vibration frequencies in the range of 1,000 to 2,500 per minute.

Static Operation Mode: The first several passes of any vibratory roller should be in the "static" mode. This procedure acts as a breakdown roller for better control of initial compaction prior to vibratory rolling to required density. Self-propelled vibratory rollers can operate at normal speed in either direction. This is an advantage where turnaround space is so limited that the towed types of rollers have to be pulled across a soil subgrade or shoulder which can result in tracking mud onto the base.

Vibrator Efficiency: The efficiency of vibrating rollers is influenced by three factors:

- Vibration unit characteristics
  - Amplitude (total vertical motion)
  - Frequency (vibrations per minute) of force applied to the layer being compacted
- Speed of travel
- Static drum weight

The actual force hitting the surface being compacted is a function of the amplitude of roller movement and the static drum weight. The drum weight and amplitude of movement should be adjusted according to lift thickness and the strength of the material beneath the lift—the thicker the lift the higher the amplitude. High amplitudes of vibration should not be used on a thin lift, especially if the lift is being placed on a weak subgrade. Repeated passes at high amplitude tend to fracture particles of aggregates, producing degradation and a change in the particle size distribution.

Vibratory Frequency: Vibratory frequency is controlled independently from both amplitude and speed of travel. Speed of the roller and vibration frequency together govern the number of impacts applied per linear foot of travel. Roller speeds should be kept between 1.5 and 3 miles per hour (the walking speed of a person) resulting in about seven to 16 vibration impacts per foot of travel. Table 17.6 indicates the numbers of impacts per linear foot applied at typical frequencies and forward speeds. Note that the higher the frequency or the lower the speed, the greater the number of impacts applied per linear foot of travel.

Table 17.6 Vibratory Roller Impacts per Linear Foot[12]

Frequencies Cycles per Minute	Roller Speed in Miles per Hour (Feet Per Minute)		
	1.5 (132)	2.5 (220)	3.5 (308)
1000	7.6	4.5	3.2
1200	9.1	5.5	3.9
1400	10.6	6.4	4.5
1600	12.1	7.3	5.2
1800	13.6	8.2	5.8
2000	15.2	9.1	6.5

Caution: It is possible to over-vibrate some materials and pump excess moisture and fines into the base or through the base to the surface.

In summary, vibratory rollers are available in a wide range of sizes and weights, and most are quite effective in compacting base material to adequate density. On most models, the static weight can be adjusted by the addition of surcharge weights or water for improved effectiveness. Experienced contractors learn to adjust all factors—drum weight, amplitude, frequency and speed of travel—in order to reach target density with minimum effort.

2. **Pneumatic-Tired Roller:** Rubber-tired rollers are available in a wide variety of weights and designs, and commonly are used on cohesionless soils as well as aggregate bases. Their effectiveness on crushed-stone bases is dependent upon the pressure and kneading action of the tires. Pneumatic-tired rollers have the advantage of achieving uniform density even when the underlying surface is uneven.

3. **Smooth-Wheeled Rollers:** Heavy steel-wheeled rollers often are used on stone base construction, either for initial breakdown rolling close behind the spreader or for final finishing teamed with a motor grader. Steel-wheeled rollers are less effective than vibratory rollers in achieving uniform compaction of base layers greater than 4 to 6 inches thick. On thicker lifts they tend to create a hard crust at the top of the lift and leave the bottom at a lower density, which is often less than required. Smooth-wheeled rollers can be used, however, if the layer is built up gradually in thin lifts.

4. **Sheepsfoot Rollers:** Sheepsfoot rollers are not suited to compaction of stone base and may tend to degrade the aggregates. Sheepsfoot rollers are used effectively in compacting cohesive subgrades such as clays, silts and sandy silts.

5. **Other Compaction Equipment:** Specialty type compactors can be used in narrow, tight areas around street manholes, close to curbs, retaining walls or other structures. Specialty compactors include trench rollers, small hand-propelled vibrating rollers or pads and pneumatic tampers.

Whatever equipment is used for compacting aggregates base, it should be proved effective by checking the density achieved against a standard laboratory maximum density determined on the same material and corrected for oversize particles as previously described.

Field Compaction Control: Consider the use of the laboratory compaction results shown in Figure 17.2 for controlling compaction in the field. Assume 100 percent of AASHTO T-180 density is specified as the required compaction level to be achieved in the field. Then the required dry density that must be attained in the field is 141 pcf, which is the maximum dry density obtained from the AASHTO T-180 laboratory density test. To achieve this density, a moisture content is required very close to the optimum, which is 5.7 percent. As a second example, the specified density for another project is 97 percent of T-180 maximum dry density. The required dry density for this compaction level is 141 pcf (0.97) = 137 pcf. To achieve this density in the field, the required moisture content is determined from the moisture-density relationship shown in Figure 17.2 and should be between approximately 4 and 9 percent.

This example illustrates the very important concept that the moisture content must be within a certain range to be able to achieve the required density in the field. For cohesive soils the range in moisture content is obtained from density tests. For aggregates material, compaction tests give, at best, a general indication of required moisture content; use of a control strip is quite useful for determining optimum moisture. If the moisture content is outside this optimum range, no matter what is done it is not likely that the required density can be achieved. Also, as the specified compaction level approaches 100 percent of T-180 maximum dry density, the allowable variation in moisture content becomes smaller.

Density Specification: Construction specifications should define a final target density as a percentage of the standard compacted density established for a particular class of service required. For example, 96 percent of AASHTO T-180 maximum dry density might be considered quite adequate for relatively light traffic or for a subbase layer well below finished grade. A density of 96 percent of AASHTO T-180 is totally inadequate for heavier traffic in the top 8 to 12 inches below the first layer of the asphalt concrete. For such service unbound aggregates should be compacted as close as possible to the maximum density attainable in the field by methods described in subsequent sections. This level of compaction corresponds to at least 100 percent of AASHTO T-180 maximum dry density.

Density Problems Caused by Gradation Changes: Density control problems are encountered if the bulk of the material being placed in the field is appreciably different in gradation from the material used in either the control strip or in the laboratory to establish the reference density. If the aggregates placed in the field is deficient in fines, it cannot be made to reach the target density established using a more densely graded sample or control strip. Hence, careful control on aggregate grading is required throughout construction.

Field Moisture Control

Compaction of any soil or graded aggregates can only be accomplished when the moisture content of the material is within the allowable range of moisture contents as discussed earlier in this section.

Ideally, moisture should be uniformly distributed through the base material as it is produced and stockpiled at the plant or as moisture is introduced as the material goes through a pugmill mixer just prior to loadout for delivery to the job. This moisture content must be maintained until the target density has been reached. If the moisture is too low, water must be added using water trucks with spray nozzles. If the moisture content is too high, water must be removed by either air drying naturally, or by discing or blading the material.

Effective Compaction Control

Aggregates base must be compacted to the specific target density established as previously discussed either in the laboratory or on a field control strip. The same gradation of aggregates must also be used throughout the job and maintained within close tolerances as required, for example, by the guide specifications given in Section 17.3. *Any change in material source or processing requires submission of a new job mix formula and the establishment of a new target density.*

Target Density: Where target density is determined in the laboratory, use of a minimum of 100 percent T-180 is recommended. Proper correction for oversize particles should be provided, as shown in Figure 17.3. Where the target density is determined by means of control strips, the construction process must be capable of producing an average density at least equal to 100 percent of AASHTO T-180, based on 10 nuclear density tests taken at random locations. Sections of base subsequently constructed should be compacted to an average of at least 98 percent of the target density, based on five density tests made at stratified random locations. In addition, the density at any one location should be required to reach at least 95 percent of the target density. For less important work, the 98 percent requirement might be relaxed to 95 percent, but should still be based on the AASHTO T-180 test or the equivalent from a control strip.

Field Density Tests: To assure adequate compaction, field testing is conducted for in-place density. Density tests are made most rapidly by means of a nuclear moisture-density gauge. Preferably, the nuclear moisture-density gauge should be operated in the *direct transmission mode* to reflect the average wet density of the full depth of a lift. The *backscatter method* is influenced mainly by the top 1 inch of material immediately beneath the detector. AASHTO Methods T-238 and T-239, described briefly in Chapter 3, are used for measuring density and moisture, respectively. Figure 17.9 indicates the two modes in which nuclear testing is carried out.

Other field density test methods involve removing and weighing about ⅒ ft^3 of the compacted aggregates and measuring the volume of the hole from which it is taken. The water balloon method (ASTM D 2167) and the sand cone method (ASTM D 1556) are two principal methods used to measure this volume. The water balloon method is considerably more precise than the sand cone method for a roughsided hole in a coarse aggregates base.

Regardless of the method used to measure in-place density, the moisture content must be measured and the wet density converted to dry density, i.e., the density test results are reported in terms of unit weight of dry solids. This is done automatically by the nuclear method, although the moisture measurement is influenced primarily by the top 1 inch of the in-place material. Determination of the volume of the hole requires drying a sample of the material removed over some type of heating element, such as a portable gasoline stove, as described in ASTM Test Method C 566.

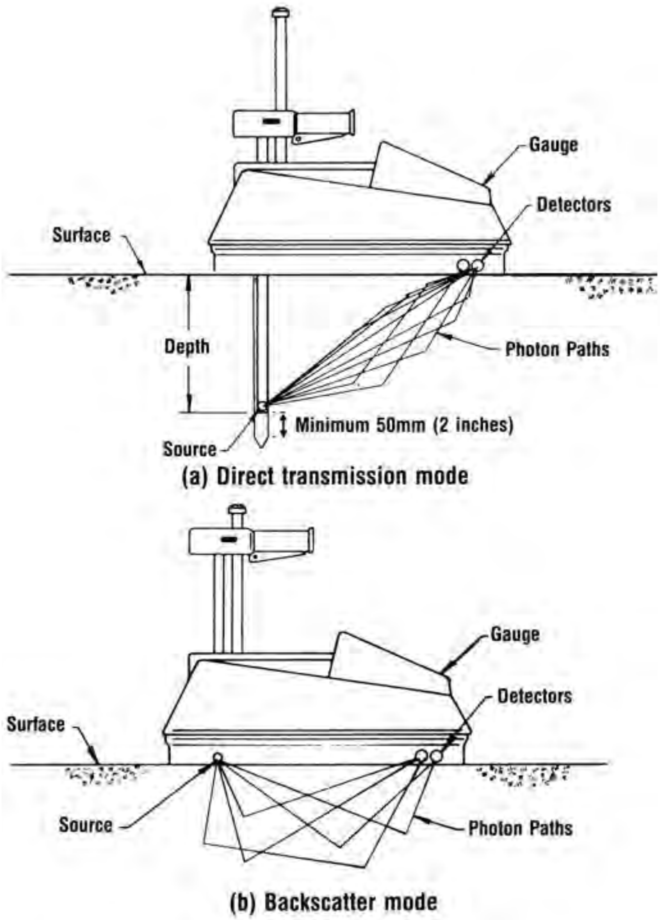

Figure 17.9 Nuclear density gauge geometry.[13]

Grade Control

The compacted base should carefully be checked to see that it is true to planned alignment, grade and slope. If the base has been used as a haul road, extreme care is essential to restore its shape and integrity. Any dirt tracked onto the base must be removed and any raveled or potholed areas must be reshaped and recompacted. An asphalt prime coat or the first paving layer should be applied promptly after completion of the base to provide maximum protection from weather and wear. The surface of the completed base should have no deviations in excess of ½ inch when checked with a 10-foot straight edge, as required in the Guide Specifications for Component Materials given in Section 17.3.

Aggregates Handling, Stockpiling and Transportation

Aggregates Grading

Aggregates grading and grading controls are important properties of aggregates in most applications requiring high quality materials. The following technology advances in pavement construction require the use of high-quality aggregates:

- Asphaltic concrete mix designs such as Superpave™ and SMA mixtures
- More restrictive requirements on portland cement concrete such as durable, high strength mixtures or super flat floors
- High strength aggregates bases that are compacted to the required density in layers up to 21 inches thick.

As aggregates are moved, stockpiled or shipped from point to point, a conscientious effort must be made to protect the integrity of product quality. Attention to the details of handling aggregates material should result in a product that is clean, uniformly graded, not segregated and meets specifications.

Segregation

Generally, segregation occurs during stockpiling and handling. Segregation is the separation of aggregates particles into various size ranges such that the grading is not uniform throughout the product. Segregation does not take place with single size materials. Frequently, blending together several different single size stones, in fractionated plants or at the concrete or asphalt plant, is an excellent method to minimize segregation. However, many products such as graded aggregates base are composed of many different size particles. The wider this particle size difference, the more prone aggregates are to segregation.

Aggregates Uses

The use of aggregates can be classified into four broad categories (1) graded aggregates base, (2) aggregates for asphalt concrete (3) aggregates for portland cement concrete and (4) other uses with specific gradation, quality and cleanliness requirements. Since each of these categories has different physical characteristics and end users, specific techniques must be employed for each classification to ensure compliance with the specifications and required product uniformity.

Considerations at the Plant: All six elements in the aggregates production process must be appropriately considered. Good overburden stripping practices remove undesirable material. Efficient rock crushing begins in the quarry with a well-planned and executed drilling and blasting program. Properly shot rock passes through the plant with more ease than poorly shot rock thus achieving better control of grading in the final product. Likewise, all stages of plant processing from primary crushing to screening and tertiary crushing affect aggregates grading and its variability.

Handling and Stockpiling: Control of aggregates grading does not end at the plant. Minimizing aggregates degradation and segregation are essential considerations as aggregates are handled, stockpiled and transported. Aggregates degradation is the abrading or breaking of an aggregate particle into smaller sizes. *Aggregates degradation* results in a change in grading. Degradation is a function of the mineralogical properties of the rock, the size or mass of the particle, aggregates grading and the method used to handle the stone. For example soft, friable limestones usually generate more minus 75 μm fines when handled than do igneous or hard limestones. Certain coarse grained igneous materials, however, readily degrade into "sand" size fractions during handling or stockpiling. If degradation creates excess fines and grading problems, additional screening and washing may be required to bring product grading back into specifications. *Thus, it is important to minimize the frequency of handling or control aggregates handling methods.*

Handling Clean Aggregates: A summary of what to do and what not to do when handling and stocking clean aggregates is given in Table 17.7. Clean aggregates are defined as aggregates with a minimum of fines.

Table 17.7 Guidelines for Handling and Stockpiling Clean Stone

DO's	DON'Ts
1. Place product in a single lift of tightly spaced truck dumps	1. Don't form a cone-shaped pile of aggregatess, i.e., cone up.
2. Stockpile only as high as a loader can reach	2. Don't operate equipment on the aggregates
3. Keep aggregates sizes separated	3. Don't overlap stockpiles of different sizes
4. When loading, keep loader bucket up at least 6-in. off the surface	4. When loading, don't dig up the lowest 6-in. of aggregates
5. Remove any contamination sources	5. Don't stockpile where material can become contaminated
6. Keep stockpiles (cones) small	6. Don't empty bins

Graded Aggregates and Asphalt Aggregates

Handling Procedures: Graded aggregates and asphalt aggregates contain a wide range of particle sizes, depending upon the product specified. Both of these materials contain a blend of coarse and fine aggregates, and include some minus 75 μm material. Procedures for handling these materials differ slightly from those specified in Table 17.1 for clean stone. For example, equipment generally can be operated on these materials without adversely affecting the final product. However, graded aggregates base and asphalt aggregates are much more susceptible to segregation because of the wide range of particle sizes in the grading. Thus, do's and don'ts listed above also apply for these materials except equipment can, usually, if necessary, be operated on a limited amount on the stockpile.

Moisture: Dry aggregates segregate more than moist material. Thus, some moisture in aggregates significantly reduces segregation. *However, it is important to limit moisture in asphalt aggregates to minimize drying cost, and to limit the moisture content of aggregates base to no more than the optimum moisture content. A pugmill is a very effective method to blend aggregates and water into a uniform product.*

Pugmilling: Segregation often occurs during the placement of graded aggregates base. Segregation is minimized using material that has been pugmilled at optimum moisture and placed using a spreader box. If other methods are used such as truck placement or grader spreading, careful attention must be given to each phase of the placement operation to assure that an unacceptable level of segregation does not take place.

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Chapter 18
Quality Control, Sampling and Testing

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18.1 Introduction

A contract for a construction project is a legal document between the contractor and the owner agency. The aggregates producer is a supplier of the aggregate to the contractor, and ultimately to the owner's project. The aggregates producer may have a sales agreement with the contractor, but he does not have a legal contract with the owner agency. As a consequence, quality control activities and test results determined by the aggregates supplier frequently are not considered acceptable to the owner agency except for general information purposes.

When a problem with aggregates quality is experienced on a project, the supplier's process control data can be used to support his position that the contractor was provided a quality aggregates material, and that the contractor needs to investigate other causes of the aggregates quality problem. Potential causes of a quality problem include segregation during handling and transport, stockpile contamination at the contractor's worksite due to mixing of different aggregates products, wind blown contamination, contamination from other sources, use of the wrong aggregates product and degradation due to improper stockpiling practices at the worksite or on the project grade.

Statistically based quality process control is routinely used in the construction materials industry. With the increased use of statistically based specifications, an adequate knowledge of production variability is crucial to understanding the true quality of the material.

A key item pertaining to quality is a consistent product. Produced materials must normally meet a target or specified grading. However, even if the target grading is achieved, excessive variability (non-consistency) can cause problems for end users, such as hot mix asphalt (HMA) producer and ready-mix concrete producers.

Customers are demanding more consistency from purchased products. When consistent products are supplied, the relationship between the aggregates supplier and customer is strengthened.

This chapter provides an overview of statistical quality process control terms and illustrates the importance of consistency in the supplied product. It includes discussion of quality control and quality assurance, statistical analysis procedures, percent within limits (PWL) and product acceptance plans. Additionally, the variability of various products is examined against specification requirements.

The chapter also contains a detailed discussion of proper sampling and testing procedures to provide data that can be used to accurately assess the quality control of the production process at a pit or quarry, and for quality acceptance. Procedures are provided for obtaining representative samples and calculating pertinent sample statistics for use in evaluation and decision making regarding the quality of the total population (*universe*). Factors influencing required testing frequency are defined. Procedures are included for establishing testing frequency and establishing conformance with specification requirements. Lastly, techniques for construction and use of *process behavior charts* for determining when the production process is out-of-control are reviewed, and example charts are given.

18.2 Reasons for Aggregates Evaluation

Tests and evaluations are performed on aggregates to determine information about the physical and chemical properties of the aggregates. Five specific reasons why these tests and evaluations are conducted are as follows:

1. **To evaluate the potential quality of a proposed aggregates source.** The evaluation of a potential quarry site or gravel pit is a typical example. As much information as possible must be determined for the material from a prospective quarry or pit to make an intelligent and financially sound decision as to the purchase of a property. Some typical questions that must be answered are: Can concrete aggregate be produced? Will the material be suitable for erosion-control stone? Is it suitable for skid-resistant pavement surfaces? Will the fines from crushing satisfy the sand requirements for portland cement concrete or asphalt concrete, or both? What challenges do the prospective reserves mean for the mine planner? What ledges within the quarry will not produce suitable product? It also should be realized that samples obtained and processed in a laboratory may not simulate material obtained from actual large scale production processing.

2. **To determine compliance with project specification requirements.** Prior to the bidding for a particular project, a series of tests frequently are conducted to evaluate whether or not the aggregates complies with project specifications. The specification may call for a minimum percentage passing a particular sieve, a maximum unit weight, Los Angeles degradation resistance or other aggregates properties.

3. **To ensure through quality controls that the intended product is being produced and to monitor performance of the production plant.** Tests are conducted at the production plant site to monitor production and advise operating personnel of problems or potential problems. Oversize material in stockpiles indicates the possibility of a hole in one or more screens. A material consistently too coarse or too fine indicates that crusher adjustments may be required. Material evaluation also is performed to aid in adjustment of the crushers, and measurement of screening efficiency to permit the balancing of plant production with sales projections.

4. **To assure the customer is receiving the same material that is being produced at the production plant site.** Periodic tests are conducted by either an asphalt concrete producer, portland cement concrete producer or other users of aggregates to monitor material delivered to their plants. For the asphalt concrete producer, gradation changes in the delivered materials can

affect the setup of the asphalt plant. A change in the job-mix formula for the asphalt concrete could be required with a change in asphalt cement content. For the contractor placing an aggregates base, a significant change in gradation means that a change in the optimum moisture content and perhaps a change in the compaction effort are required to meet the density specification.

5. **To obtain measurements of the physical properties (parameters) used by the engineer in design of pavements, portland cement and asphalt concrete mixes, foundations, etc**. Examples of the use of several physical properties are the specific gravity of an aggregates is used when calculating the absolute volume occupied by that aggregates in a concrete mix design and the California Bearing Ratio (CBR) of a base is often used in the thickness design of a flexible pavement system. Detailed discussion of these physical properties can be found in Chapter 3.

Sensitivity, Accuracy and Precision

When evaluating test results, one must be aware of the sensitivity, accuracy and precision of the test method. The *sensitivity* is the effect that small changes in the variable being measured have on the test value obtained. The testing equipment used must have a high degree of sensitivity. Without it, the test results are either meaningless or evaluated incorrectly. *Accuracy* is how close to the true value an answer can be obtained using a given piece of equipment and test procedure. *Precision* is the reproducibility of the test results.

Quality

The properties of aggregates used in unbound granular base or in aggregates-binder mixtures are important to the performance and life of the system in which they are used. Control of the quality of aggregates during production and construction is essential for good performance of the resulting construction. *Quality* is the level of specific physical or chemical properties (or both), as determined using established criteria, that aggregates possesses after being processed into specific products for use in construction.

18.3 Quality Control / Quality Assurance Overview

Quality control and quality assurance (QC/QA) are terms frequently used in construction materials testing and specifications. There are varying definitions for QC/QA, but one set is provided below.

- **Quality Control** – one or more activities performed by the producer prior to, during and after production to produce and verify that the aggregates products possess properties that equal or exceed the level required by project specifications. Control of product quality during the manufacturing or production process must be performed by planned and pre-established methods. Testing is performed by the aggregate producer, by the contractor or by a contractor's representative.

- **Quality Assurance** – one or more activities performed by the receiver or owner agency to verify and assure the agency that the aggregates products that either will be or have been used in a project possess properties that equal or exceed the quality level desired or specified. QA activities are put in place to assure that the contractor/supplier's QC process is working. QA is an established system of sampling, testing and analysis conducted by or for the owner.

To illustrate the concept of QC/QA consider a project where an aggregates supplier is shipping crushed aggregates base for a state highway project. The contractor, the aggregates supplier and the owner of the highway being constructed are all interested in achieving quality. The supplier normally conducts testing on material to be shipped as it is being produced at the production plant as part of his internal QC testing program. Other QC testing may be conducted based on the requirements of the owner agency. QA testing is performed by the owner agency to gain assurance that the supplied aggregates base at the project site meets project specifications.

One key to a successful QC/QA program is correct product sampling. The supplier's desire is to produce a quality product and the owner's desire is to obtain a quality product. The only way to be 100 percent certain of product quality is to sample and test 100 percent of the product. This is unrealistic and does not happen. In actuality, the product is randomly and representatively sampled at a prescribed rate and then tested.

18.4 Sampling Terms

When discussing sampling within statistical specifications, several terms must be understood. These terms are briefly presented below along with examples.

Population

A population is defined as any quantity of material produced at a given aggregates production plant with the *same* feed material and *without change* in plant setup or operating parameters. For example, it could be the total amount of aggregates base produced for a highway project, or all product produced within a given reference timeframe, or some smaller increment of tonnage based on construction schedule or time. If nothing changes during the production process, samples from different locations on a project can be combined and treated as coming from the same population. However, if something changes to the material (plant setup, weather, etc.); the material at each location may represent different populations and should not be combined.

Sample

A sample is any subset of a population. For the above population, one possible sample would be the first 20 percent of aggregates base produced. Another smaller sized sample may consist of material taken at prescribed intervals (e.g., every 2000 tons of produced base) during a day's production. A sample can represent any quantity of product, but its use is to gain an estimate of the average and variability of a property or characteristic, such as gradation, for the population. As the sample size increases, the population estimate becomes better.

Bias

One of the most important items to avoid in sampling is bias. Bias indicates that some portion of the population has more or less of a chance of being sampled than the remainder. For example, taking only the first 20 percent of the produced base would be an example of a biased sample. Another example of bias would be purposely taking samples of material that appear to either be "in" or "out" of specification. Biased samples can be unfair to the contractor, or the owner, or both, and have no place within a quality control and acceptance program.

Random Sample

To truly be a representative sample, every portion of the population should have an equal chance of being sampled. When this occurs, the sample is said to be random. A sample that is not randomly determined and obtained has bias present. Random sampling is a must for an effective quality program. To obtain a random sample, the sample location must be selected using a random number table or other generator (e.g., calculator random number key).

Lot

In construction materials QC/QA programs, produced material is normally divided into lots for testing and acceptance. Generally, a lot is a subset of a population. However, if the population is small, the lot could be the entire population. An example of a lot would be one day's production of aggregates base for a highway project.

Sublot

A lot is typically further divided into smaller portions called sublots. If a day's production of aggregates base is a lot, a sublot may be the production during each three-hour time increment. Alternately, it also could be every 500 tons produced during the day. There are many ways to define lots and sublots, but the intent and purpose are the same. By taking samples within the lot based on time or tonnage, the random sampling is "stratified." Stratification is important to "spread" the sampling over the lot. Theoretically, if four samples are required for a lot, those samples could be "bunched" to where they fall close together (e.g., all before 10:00 a.m. or before 500 tons). The result is the remaining material is not being tested, which could be unfair to both the owner and the contractor.

Homogeneous Data

The results obtained from analyzing a set of data are of little value from the standpoint of interpretation unless the data are "good." Data are good only if they satisfy certain requirements. To be useful for analysis, individual observations of a set of observations that are treated as a single group should all be made under essentially the same conditions. Thus, all of the material or product must be produced under essentially the same conditions. Such data are described as being *homogeneous*.

A given sample of data, under some conditions, may consist of two or more sub portions collected under different test conditions or representing material produced under different conditions. This sample of data should be considered as two or more separate subgroups of observations, each to be treated independently in the analysis. Merging of such subgroups leads to a composite sample that is of little practical value.

If data are obtained under controlled, homogeneous conditions, the observed frequency distribution can, for most practical purposes, be represented by a theoretical curve, such as defined by the *Normal law*.

18.5 Statistical Parameters

Knowledge of a pattern of variation of the production process is obtained if a sufficient number of samples are taken and the test results are analyzed. This knowledge of the production process can be used to good advantage in controlling future production.

In condensing and summarizing data contained in the frequency distribution of a set of observations, two important characteristics of the distribution are often determined: the *central value* about which the observations have a tendency to center, which is called the arithmetic mean, $\bar{X}$, and the *spread* or dispersion of the observations about the central value, which is described using the estimate of the *standard deviation(s)* of the population based on the samples.

To evaluate material variability, basic statistical analysis terms and procedures should be understood. If two or more test results (or data) are obtained, several statistical terms can be calculated. These include the mean, variance, standard deviation and coefficient of variation. These terms are determined for the data provided in Table 18.1 and the calculations provided in Table 18.2.

Table 18.1 Example Data for Statistical Parameter Illustration

Screen Size	Specification	Percent Passing						$\bar{X}$	s
		Test Number							
		1	2	3	4	5	6		
½"	25-60	42.8	50.1	46.3	39.5	50.1	47.2	46	4.19

Mean

The mean ($\bar{X}$) is the average of the sample data set and is calculated by summing all the data (X) and dividing by the number of data (n), as shown in Equation 18-1. The sample mean is an estimate of the population mean.

$$\bar{X} = \sum_{i=1}^{n} \frac{X_i}{n} \tag{18-1}$$

Table 18.2 Statistical Calculations

Result	% Passing	$X_i - \bar{X}$	$(X_i - \bar{X})^2$
1	42.8	-3.2	10.24
2	50.1	4.1	16.81
3	46.3	0.3	0.09
4	39.5	-6.5	42.25
5	50.1	4.1	16.81
6	47.2	1.2	1.44
Sum	276.0		87.6
N	6.0		
Mean	46.0		
s^2	17.53		
s	4.19		
COV (%)	9.10		

Variance

Variance (s^2) is a measure of the variability of the sample test data with respect to the mean value, as calculated in Equation 18-2. The sample variance is an estimate of the population variance.

$$s^2 = \frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{(n - 1)} \tag{18-2}$$

where

X_i = individual test value
$\bar{X}$ = average of sample data set
n = number of data points in set

Standard Deviation

Standard deviation (s) is a common measure of variability and is the square root of sample variance. It is calculated as shown in Equation 18-3. The sample standard deviation is an estimate of the population standard deviation.

$$s^2 = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{(n-1)}} \quad (18\text{-}3)$$

where

s = standard deviation of sample
X_i = individual test value
$\bar{X}$ = average of sample data set
n = number of data points in set

Coefficient of Variation

Coefficient of variation (COV) is a calculated number that normalizes sample variability with respect to the average. Consider the case where the standard deviation for the percent passing the No. 4 and No. 200 sieve is the same. While the variability is the same, the impact of the variability is much great for the No. 200 sieve than the No. 4 sieve. Calculation of COV is a method to better define the standard deviation when compared to a mean value. Coefficient of variation is the standard deviation divided by the mean value, as shown in Equation 18-4.

$$COV = \left(\frac{s}{\bar{X}}\right) 100 \quad (18\text{-}4)$$

where

COV = Coefficient of Variation
s = standard deviation of sample
$\bar{X}$ = average of sample data set

Standard Error of the Mean (SEM)

Another commonly used parameter is the standard error of the mean (SEM). If you have a population of 100 values and obtain many samples of size n, the deviation for the means of these samples will be less than the standard deviation for the individual data that comprises the population. In other words, the distribution of the means is "tighter."

Standard error of the mean is the standard deviation divided by the square root of the number of samples. It describes the variability of sample means comprised of "n" samples. The SEM becomes smaller as the sample size increases. The greater the sample size, the closer the sample mean is to the population mean. SEM is calculated as shown in Equation 18-5.

$$SEM = \frac{s}{\sqrt{n}} \quad (18\text{-}5)$$

where

s = standard deviation of sample
n = number of data points in set

18.6 Histogram Development and Normal Distribution

Repeated measurements on samples taken from natural populations produce a characteristic frequency distribution. Test values are clustered around a central value and the frequency of occurrence declines away from the central value.

A histogram is used to graphically illustrate the frequency of data between certain established ranges (commonly referred to as *bins*). Figure 18-1 illustrates a histogram for a set of percent passing data (N=500 test results), with a mean of 49.96 percent and standard deviation of 4.86 percent. The value at the top of the respective bars (in Figure 18.1) indicates the number of test results within a given bin.

Test parameter data for construction materials typically follow a normal distribution. This means that if a group of test data were plotted based upon their frequency of occurrence, the resulting histogram would be "bell shaped."

A frequency distribution curve graphically depicts the frequency of occurrence of test values of the same magnitude over the range of test values that have been determined. A normal distribution can be fitted to the histogram data. The distribution will have a mean or average value and standard deviation, based upon the variability of the test data depicted in the histogram. A *normal curve* having the bell-shaped symmetrical form is illustrated in Figure 18.2. The curve extends from minus infinity to plus infinity. However, most of the area under the normal curve is included within the limits of $\bar{X}$+3 s, where $\bar{X}$ is the arithmetic mean and s is the estimate of the standard deviation.

A normal distribution has 50 percent of data above and has 50 percent of data below the mean value. Furthermore, approximately 68 percent of the data lies within the mean ± 1 standard deviation, 95 percent within the mean ± 2 standard deviations and 99.7 percent within the mean ± 3 standard deviations. The ranges for the mean ± 1, 2 and 3 standard deviations are shown in Figure 18.2.

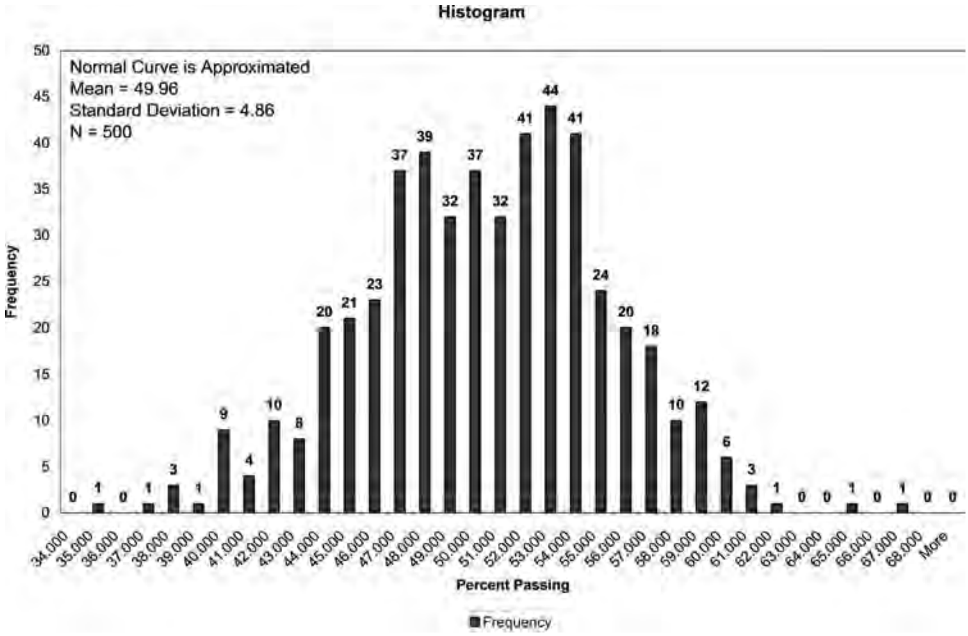

Figure 18.1 Histogram Example

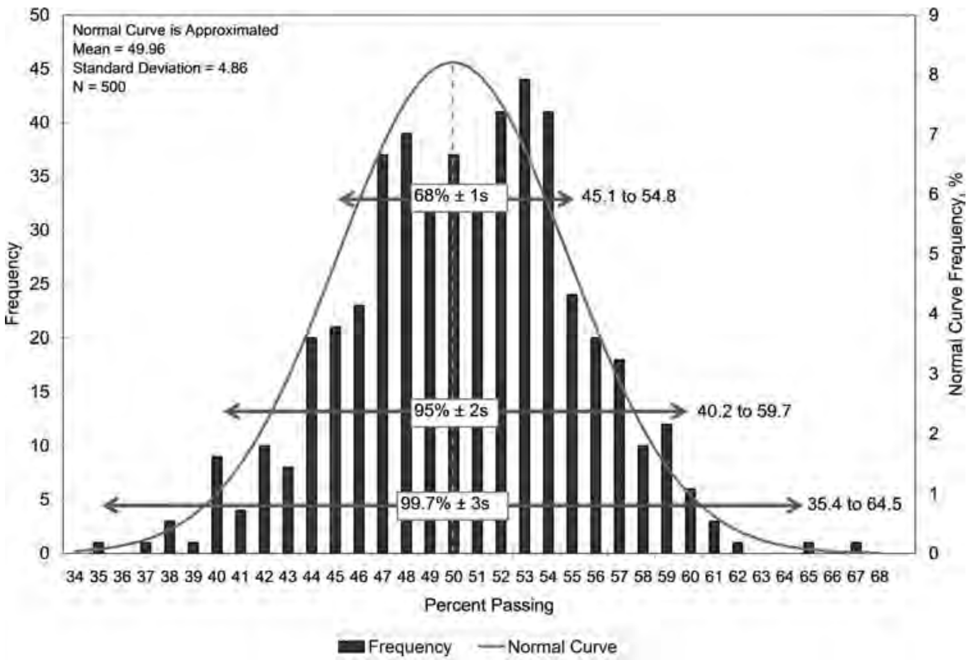

Figure 18.2 Normal Distribution Curve Illustration

18.7 Probability of Sample Occurrence in a Normal Distribution

The concept of normally distributed data allows analysis and prediction of data within certain ranges of the distribution. To determine the probability of data occurring at various points within the normal distribution, a "Z-value" is normally calculated and utilized. The Z-value is the number of standard deviations a given value is above or below the mean.

Consider an example where the population average is 27.3 with a standard deviation of 2.7. It is desired to know the probability that a single random sample will fall between 10 and 30. In order to evaluate this problem, two Z-values must be calculated, one each for the lower and upper limits. The basic form of the z-value equation is shown in Equation 18-6. In Equation 18-6, x is the value to evaluate, μ is the population mean and σ is the population standard deviation.

$$Z = \frac{X - \mu}{\sigma} \qquad (18\text{-}6)$$

where

Z = the number of standard deviations a given value is above or below the mean
x = the value being evaluated
μ = the population mean
σ = standard deviation

In this example, the two z-values for the specification values are calculated as shown below.

$$Z = \frac{10 - 27.3}{2.7} = -6.24$$

$$Z = \frac{30 - 27.3}{2.7} = 1.00$$

After the Z-values are calculated, a standard normal table, as shown in Table 18.3, is used to determine the probability of a single sample outside the specification limit. Not all standard normal distribution tables are set up in the same format so care must be taken when using them. Table 18.3 provides the upper normal curve tail area probabilities. Notice that all z-values in Table 18.3 are positive. This is just a way to reduce the size of the table. A negative z-value indicates tail areas to the left side or less than the mean. Positive z-values indicate values to the right side or greater than the mean.

Upon entering Table 18.3 with a z-value of 6.24 it is apparent that the highest z-value is 2.99. This is because the *mean ± 3 standard deviations* encompass 99.7 percent of the data under the normal curve. There is no statistical chance or probability that a single result will be below the lower value of 10. For the upper value of 30, the -value is 1.00, which yields a 15.87 percent probability of a single sample being greater than 30. Consequently, there is an 84.13 percent probability (100 – 15.87) of a single sample being within the 10 to 30.

Table 18.3 Standard Normal z-Distribution Probability Table

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641
0.1	0.4602	0.4562	0.4522	0.4483	0.4443	0.4404	0.4364	0.4325	0.4286	0.4247
0.2	0.4207	0.4168	0.4129	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859
0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3594	0.3557	0.3520	0.3483
0.4	0.3446	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121
0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776
0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451
0.7	0.2420	0.2389	0.2358	0.2327	0.2296	0.2266	0.2236	0.2206	0.2177	0.2148
0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867
0.9	0.1841	0.1814	0.1788	0.1762	0.1736	0.1711	0.1685	0.1660	0.1635	0.1611
1.0	0.1587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379
1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170
1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1038	0.1020	0.1003	0.0985
1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0869	0.0853	0.0838	0.0823
1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0721	0.0708	0.0694	0.0681
1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559
1.6	0.0548	0.0537	0.0526	0.0516	0.0505	0.0495	0.0485	0.0475	0.0465	0.0455
1.7	0.0446	0.0436	0.0427	0.0418	0.0409	0.0401	0.0392	0.0384	0.0375	0.0367
1.8	0.0359	0.0351	0.0344	0.0336	0.0329	0.0322	0.0314	0.0307	0.0301	0.0294
1.9	0.0287	0.0281	0.0274	0.0268	0.0262	0.0256	0.0250	0.0244	0.0239	0.0233
2.0	0.0228	0.0222	0.0217	0.0212	0.0207	0.0202	0.0197	0.0192	0.0188	0.0183
2.1	0.0179	0.0174	0.0170	0.0166	0.0162	0.0158	0.0154	0.0150	0.0146	0.0143
2.2	0.0139	0.0136	0.0132	0.0129	0.0125	0.0122	0.0119	0.0116	0.0113	0.0110
2.3	0.0107	0.0104	0.0102	0.0099	0.0096	0.0094	0.0091	0.0089	0.0087	0.0084
2.4	0.0082	0.0080	0.0078	0.0075	0.0073	0.0071	0.0069	0.0068	0.0066	0.0064
2.5	0.0062	0.0060	0.0059	0.0057	0.0055	0.0054	0.0052	0.0051	0.0049	0.0048
2.6	0.0047	0.0045	0.0044	0.0043	0.0041	0.0040	0.0039	0.0038	0.0037	0.0036
2.7	0.0035	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026
2.8	0.0026	0.0025	0.0024	0.0023	0.0023	0.0022	0.0021	0.0021	0.0020	0.0019
2.9	0.0019	0.0018	0.0018	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014

It is frequently useful to evaluate the precision and accuracy of the grading of produced aggregates material against agency specifications. Such an evaluation provides the producer a good understanding of the percentage of time the material will be expected to be within specification. A good example of using this approach would be in determining what material should be provided for a given project. Perhaps there are multiple sources available, but it is desirable to determine which location has the greatest chance of providing material within specification.

Z-Value Example Using Virginia Base

To illustrate this, consider the 21A base material from an aggregates operation in Virginia. The Virginia DOT specification for 21A base specifies master target gradation ranges as shown in Table 18.4. Once the target gradation is established, process tolerances, shown in Table 18.5, are applied as a function of the number of tests to be obtained. Normally, Virginia specifies a lot as 2,000 tons with four stratified random samples obtained per lot. Material outside the process tolerances is subject to penalty.

Consider 21A base material with 188 gradation tests obtained from January to July, the average percent passing for the ⅜-inch sieve was 65 percent with a standard deviation of 4.7 percent. For these calculations, the 188 tests will represent the population.

The material meets the VDOT specification range of 63 to 72 percent, as seen in Table 18.4. Given an average of 65 percent, the allowable production tolerances for a single sample would be 56 to 74 percent. What would be the percent within specification for a given production average and associated variability? Figure 18.3 illustrates the *percent within specification* for averages of 60, 61, 62, 63, 64 and 65, each with standard deviations ranging from 3 to 8 percent. Figure 18.3 shows for the production average of 65 percent and standard deviation of 4.7 percent, the percent within specification would be approximately 95 percent, which is very good. In comparison, consider a case where the average remains 65, but the standard deviation increases to 8 percent. In this case the percent within specification falls to less than 75 percent. Also notice that if the average drops to 60 percent with a 3 percent standard deviation, just over 90 percent of the material would be expected to be within specification.

Figure 18.4 illustrates a similar concept, except with a sample size (n) equal to four. In the case where the number of samples is greater than one, the SEM is calculated. The SEM in this case is calculated based on the same standard deviation of 3 to 8 percent with n = 4. Immediately evident is the increased amount of material within specification compared to the n = 1 case. This is due to the average and overall variability being less and therefore a higher percentage of samples being close to the average value.

Table 18.4 Design Range for Dense Graded Aggregates

Amounts of Finer Than Each Laboratory Sieve (Square Openings*) (% by Weight)						
Size No.	**2 in.**	**1 in.**	**⅜ in.**	**No. 10**	**No. 40**	**No. 200**
21A	100	94-100	63-72	32-41	14-24	6-12
21B	100	85-95	50-69	20-36	9-19	4-7
22	--	100	62-78	39-56	23-32	8-12

** In inches, except where otherwise indicated. Numbered sieves are those of the U.S. Standard Sieve Series.*

Table 18.5 Process Tolerance for 21A Base

Process Tolerance for Each Laboratory Sieve (%)							
No. Tests	**Top Size**	**1 in.**	**¾ in.**	**⅜ in.**	**No. 10**	**No. 40**	**No. 200**
1	0.0	±10.0	±14.0	±19.0	±14.0	±8.0	±4.0
2	0.0	±7.1	±10.0	±13.6	±10.0	±5.7	±2.9
3	0.0	±5.6	±7.8	±10.6	±7.8	±4.4	±2.2
4	0.0	±5.0	±7.0	±9.5	±7.0	±4.0	±2.0
8	0.0	±3.6	±5.0	±6.8	±5.0	±2.9	±1.4

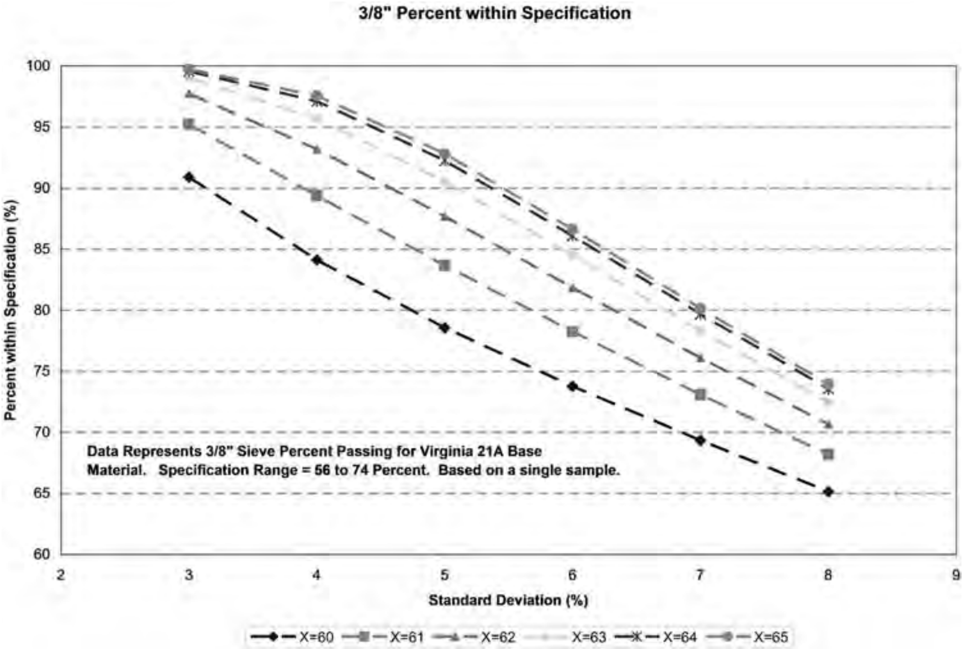

Figure 18.3 Percent within Specification for Single Sample

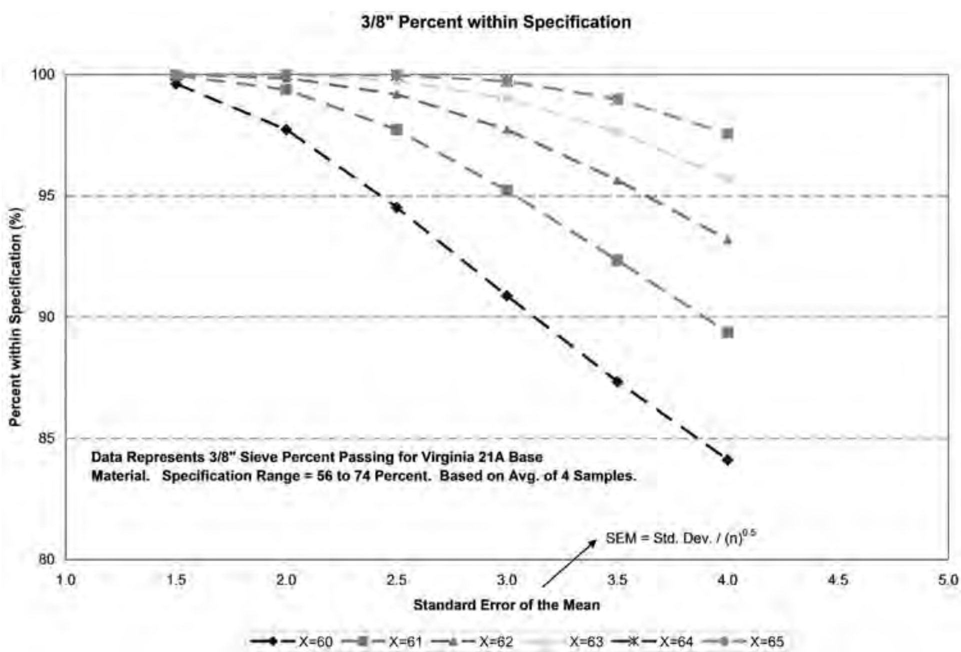

Figure 18.4 Percent Within Specification for Average of Four Samples

18.8 Specifications

Specifications represent a detailed and exact statement prescribing materials, dimensions and workmanship for something to be built, installed or manufactured. Specifications exist for the following reasons:

- Define material quality and construction required to achieve desired service life.
- Guide contractors in submission of realistic bids.
- Guide inspectors in the assurance of compliance with quality requirements.
- Form a legal agreement between owner and contractor and as such to become an integral part of a contract.

Quality specifications should be fair to the contractor and the owner agency. There are many types of specifications currently used in the construction materials industry. Among these are method, end result, QC/QA, and PWL.

Method Specification

A method specification is one where the owner establishes procedures and "methods" for the contractor. There is very little, if any, QC/QA testing for projects with a method specification. Generally, method specifications are most often used by local agencies for smaller scale projects.

Example wording of a method specification would be "...contractor shall compact the aggregates base using a 12 ton steel wheel roller making two passes..." Method specifications are very inspector intensive as inspectors must be on the job or project at all times to verify the methods are being utilized correctly. If correct methods are used, the contractor will be guaranteed payment under a method specification.

End Result Specification

End result specifications set forth requirements for the final product. Methods to achieve the end result, to varying degrees, are the contractor's responsibility. Example wording would be "...contractor shall achieve 95 percent of modified Proctor density on the aggregates base..." In such a specification there is more opportunity for the contractor to use innovative methods to achieve the desired end result.

QC/QA Specification

A QC/QA specification can be thought of as a statistically based end result specification. As mentioned previously, the contractor is responsible for QC testing and the owner responsible for QA testing. In this specification, materials are randomly and representatively sampled for sublots or lots and payment made according to adherence to specification limits. QC/QA specifications are generally written with incentives (bonus) and disincentives (pay reduction).

Percent Within Limits Specification

Percent within limits is a specification in which the contractor is evaluated based on the percentage of material produced within project specification limits. PWL is based on the assumption that construction materials variability follows a normal distribution with an associated mean and standard deviation. This mean and standard deviation are used to calculate PWL for a lot.

PWL is very similar to the concept of determining the area under the normal curve using the z-value analysis discussed in Section 18.7. The z-value analysis evaluates a selected value against the population or project mean. PWL is slightly different because it evaluates a test or lot average against specification limits. With the z-value analysis, the mean and standard deviation are known. However, with PWL the mean and standard deviation are not known for the lot in question. Only estimates of the mean and standard deviation are available. In order to determine the actual or "true" mean and standard deviation of material within a lot, it would be necessary to test all the material in the lot, which is not possible. PWL provides an alternate method to estimate the area under the normal distribution based on a random sampling plan. PWL uses a quality index (Q) value, which is very similar to the Z-value. The Q value is a function of the sample size (n), sample average ($\bar{X}$) and the sample standard deviation (s). Q values are shown in Table 18.6.

The equations used for calculating the quality indices are provided below in Equations 18-7 and 18-8. Q_u and Q_L refer to the quality indices for the upper and lower specification values, respectively. In a situation where there is only one specification value (e.g., minimum in-place density), only one quality index (Q_L) would be calculated.

$$Q_u = \frac{(U - \bar{X})}{s} \qquad (18\text{-}7)$$

$$Q_L = \frac{(\bar{X} - L)}{s} \qquad (18\text{-}8)$$

18.9 Percent Within Limits for Aggregates Base Grading

To illustrate the concept of PWL, an example for an aggregates base material is given below. Consider the case where a PWL specification was used for aggregates base grading. In such a case, the PWL for each control sieve would be calculated and a composite PWL calculated. Table 18.7 shows four cases for aggregates base grading. **Case 1** represents the grading at the mid-band of the specification range with an associated standard deviation from actual production. **Case 2** has the same average values, but the standard deviation has been increased by 50 percent. **Case 3** has an overall finer grading with the same standard deviation as Case 1. Finally, **Case 4** has same overall finer grading with the standard deviation increased by 50 percent.

Table 18.6 Percent Within Limits Values

P_u or P_L %	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10 to n=11	n=12 to n=14	n=15 to n=18	n=19 to n=25	n=26 to n=37	n=38 to n=69	n=70 to n=200	n=201 to n=x
100	1.16	1.50	1.79	2.03	2.23	2.39	2.53	2.65	2.83	3.03	3.20	3.38	3.54	3.70	3.83
99		1.47	1.67	1.80	1.89	1.95	2.00	2.04	2.09	2.14	2.18	2.22	2.26	2.29	2.31
98	1.15	1.44	1.60	1.70	1.76	1.81	1.84	1.86	1.91	1.93	1.96	1.99	2.01	2.03	2.05
97		1.41	1.54	1.62	1.67	1.70	1.72	1.74	1.77	1.79	1.81	1.83	1.85	1.86	1.87
96	1.14	1.38	1.49	1.55	1.59	1.61	1.63	1.65	1.67	1.68	1.70	1.71	1.73	1.74	1.75
95		1.35	1.44	1.49	1.52	1.54	1.55	1.56	1.58	1.59	1.61	1.62	1.63	1.63	1.64
94	1.13	1.32	1.39	1.43	1.46	1.47	1.48	1.49	1.50	1.51	1.52	1.53	1.54	1.55	1.55
93		1.29	1.35	1.38	1.40	1.41	1.42	1.43	1.44	1.44	1.45	1.46	1.46	1.47	1.47
92	1.12	1.26	1.31	1.33	1.35	1.36	1.36	1.36	1.37	1.37	1.39	1.39	1.40	1.40	1.40
91	1.11	1.23	1.27	1.29	1.30	1.30	1.31	1.31	1.32	1.32	1.33	1.33	1.33	1.34	1.34
90	1.10	1.20	1.23	1.24	1.25	1.25	1.26	1.26	1.26	1.27	1.27	1.27	1.28	1.28	1.28
89	1.09	1.17	1.19	1.20	1.20	1.21	1.21	1.21	1.21	1.22	1.22	1.22	1.22	1.22	1.23
88	1.07	1.14	1.15	1.16	1.16	1.16	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17
87	1.06	1.11	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.13	1.13
86	1.04	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
85	1.03	1.05	1.05	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
84	1.01	1.02	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
83	1.00	0.99	0.98	0.97	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.95	0.95	0.95
82	0.97	0.96	0.95	0.94	0.93	0.93	0.93	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
81	0.96	0.93	0.91	0.90	0.90	0.89	0.89	0.89	0.89	0.88	0.88	0.88	0.88	0.88	0.88
80	0.93	0.90	0.88	0.87	0.86	0.86	0.86	0.85	0.85	0.85	0.85	0.84	0.84	0.84	0.84
79	0.91	0.87	0.85	0.84	0.83	0.82	0.82	0.82	0.82	0.81	0.81	0.81	0.81	0.81	0.81
78	0.89	0.84	0.82	0.80	0.80	0.79	0.79	0.79	0.78	0.78	0.78	0.78	0.77	0.77	0.77
77	0.87	0.81	0.78	0.77	0.76	0.76	0.76	0.75	0.75	0.75	0.75	0.74	0.74	0.74	0.74
76	0.84	0.78	0.75	0.74	0.73	0.73	0.72	0.72	0.72	0.71	0.71	0.71	0.71	0.71	0.71
75	0.82	0.75	0.71	0.71	0.70	0.70	0.69	0.69	0.69	0.68	0.68	0.68	0.68	0.68	-0.67
74	0.79	0.72	0.68	0.68	0.67	0.66	0.66	0.66	0.66	0.65	0.65	0.65	0.65	0.64	0.64
73	0.76	0.69	0.65	0.65	0.64	0.63	0.63	0.63	0.62	0.62	0.62	0.62	0.62	0.61	0.61
72	0.74	0.66	0.62	0.62	0.61	0.60	0.60	0.60	0.59	0.59	0.59	0.59	0.59	0.58	0.58
71	0.71	0.63	0.59	0.59	0.58	0.57	0.57	0.57	0.57	0.56	0.56	0.56	0.56	0.55	0.55
70	0.68	0.60	0.56	0.56	0.55	0.55	0.54	0.54	0.54	0.53	0.53	0.53	0.53	0.53	0.52
69	0.65	0.57	0.53	0.53	0.52	0.52	0.51	0.51	0.51	0.50	0.50	0.50	0.50	0.50	0.50
68	0.62	0.54	0.50	0.50	0.49	0.49	0.48	0.48	0.48	0.48	0.47	0.47	0.47	0.47	0.47
67	0.59	0.51	0.47	0.47	0.46	0.46	0.46	0.45	0.45	0.45	0.45	0.44	0.44	0.44	0.44
66	0.56	0.48	0.44	0.44	0.44	0.43	0.43	0.43	0.42	0.42	0.42	0.42	0.41	0.41	0.41

Table 18.6 Percent Within Limits Values (cont'd)

P_u or P_L %	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10 to n=11	n=12 to n=14	n=15 to n=18	n=19 to n=25	n=26 to n=37	n=38 to n=69	n=70 to n=200	n=201 to n=x
65	0.52	0.45	0.41	0.41	0.41	0.40	0.40	0.40	0.40	0.39	0.39	0.39	0.39	0.39	0.39
64	0.49	0.42	0.39	0.39	0.38	0.38	0.37	0.37	0.37	0.36	0.36	0.36	0.36	0.36	0.36
63	0.46	0.39	0.36	0.36	0.35	0.35	0.35	0.34	0.34	0.34	0.34	0.34	0.33	0.33	0.33
62	0.43	0.36	0.33	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.31	0.31	0.31
61	0.39	0.33	0.30	0.30	0.30	0.29	0.29	0.29	0.29	0.29	0.28	0.28	0.28	0.28	0.28
60	0.36	0.30	0.27	0.27	0.27	0.27	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.25	0.25
59	0.32	0.27	0.25	0.25	0.24	0.24	0.24	0.24	0.23	0.23	0.23	0.23	0.23	0.23	0.23
58	0.29	0.24	0.22	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20
57	0.25	0.21	0.19	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
56	0.22	0.18	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15	0.15
55	0.18	0.15	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
54	0.14	0.12	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
53	0.11	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
52	0.07	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
51	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
49	-0.04	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.02
48	-0.07	-0.06	-0.06	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
47	-0.11	-0.09	-0.08	-0.08	-0.08	-0.08	-0.08	-0.08	-0.08	-0.08	-0.08	-0.08	-0.08	-0.08	-0.08
46	-0.14	-0.12	-0.11	-0.11	-0.11	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10
45	-0.18	-0.15	-0.14	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13
44	-0.22	-0.18	-0.16	-0.16	-0.16	-0.16	-0.16	-0.16	-0.16	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15
43	-0.25	-0.21	-0.20	-0.19	-0.19	-0.19	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18
42	-0.29	-0.24	-0.23	-0.22	-0.21	-0.21	-0.21	-0.21	-0.21	-0.21	-0.20	-0.20	-0.20	-0.20	-0.20
41	-0.32	-0.27	-0.25	-0.25	-0.24	-0.24	-0.24	-0.24	-0.23	-0.23	-0.23	-0.23	-0.23	-0.23	-0.23
40	-0.36	-0.30	-0.28	-0.27	-0.27	-0.27	-0.26	-0.26	-0.26	-0.26	-0.26	-0.26	-0.26	-0.25	-0.25
39	-0.39	-0.33	-0.31	-0.30	-0.30	-0.29	-0.29	-0.29	-0.29	-0.29	-0.28	-0.28	-0.28	-0.28	-0.28
38	-0.43	-0.36	-0.34	-0.33	-0.32	-0.32	-0.32	-0.32	-0.31	-0.31	-0.31	-0.31	-0.31	-0.31	-0.31
37	-0.46	-0.39	-0.37	-0.36	-0.35	-0.35	-0.35	-0.34	-0.34	-0.34	-0.34	-0.34	-0.33	-0.33	-0.33
36	-0.49	-0.42	-0.40	-0.39	-0.38	-0.38	-0.37	-0.37	-0.37	-0.36	-0.36	-0.36	-0.36	-0.36	-0.36
35	-0.52	-0.45	-0.43	-0.41	-0.41	-0.40	-0.40	-0.40	-0.40	-0.39	-0.39	-0.39	-0.39	-0.39	-0.39
34	-0.56	-0.48	-0.45	-0.44	-0.44	-0.43	-0.43	-0.43	-0.42	-0.42	-0.42	-0.42	-0.41	-0.41	-0.41
33	-0.59	-0.51	-0.47	-0.47	-0.46	-0.46	-0.46	-0.45	-0.45	-0.45	-0.45	-0.44	-0.44	-0.44	-0.44
32	-0.62	-0.54	-0.51	-0.50	-0.49	-0.49	-0.48	-0.48	-0.48	-0.48	-0.47	-0.47	-0.47	-0.47	-0.47
31	-0.65	-0.57	-0.54	-0.53	-0.52	-0.52	-0.51	-0.51	-0.51	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50

Table 18.6 Percent Within Limits Values (cont'd)

P_u or P_L %	n=3	n=4	n=5	n=6	n=7	n=8	n=9	n=10 to n=11	n=12 to n=14	n=15 to n=18	n=19 to n=25	n=26 to n=37	n=38 to n=69	n=70 to n=200	n=201 to n=x
30	-0.68	-0.60	-0.57	-0.56	-0.55	-0.55	-0.54	-0.54	-0.54	-0.53	-0.53	-0.53	-0.53	-0.53	-0.52
29	-0.71	-0.63	-0.60	-0.59	-0.58	-0.57	-0.57	-0.57	-0.57	-0.56	-0.56	-0.56	-0.56	-0.55	-0.55
28	-0.74	-0.66	-0.63	-0.62	-0.61	-0.60	-0.60	-0.60	-0.59	-0.59	-0.59	-0.59	-0.59	-0.58	-0.58
27	-0.76	-0.69	-0.66	-0.65	-0.64	-0.63	-0.63	-0.63	-0.62	-0.62	-0.62	-0.62	-0.62	-0.61	-0.61
26	-0.79	-0.72	-0.69	-0.68	-0.67	-0.66	-0.66	-0.66	-0.66	-0.65	-0.65	-0.65	-0.65	-0.64	-0.64
25	-0.82	-0.75	-0.72	-0.71	-0.70	-0.70	-0.69	-0.69	-0.69	-0.68	-0.68	-0.68	-0.68	-0.68	-0.67
24	-0.84	-0.78	-0.75	-0.74	-0.73	-0.73	-0.72	-0.72	-0.72	-0.71	-0.71	-0.71	-0.71	-0.71	-0.71
23	-0.87	-0.81	-0.78	-0.77	-0.76	-0.76	-0.76	-0.75	-0.75	-0.75	-0.75	-0.74	-0.74	-0.74	-0.74
22	-0.89	-0.84	-0.82	-0.80	-0.80	-0.79	-0.79	-0.79	-0.78	-0.78	-0.78	-0.78	-0.77	-0.77	-0.77
21	-0.91	-0.87	-0.85	-0.84	-0.83	-0.82	-0.82	-0.82	-0.82	-0.81	-0.81	-0.81	-0.81	-0.81	-0.81
20	-0.93	-0.90	-0.88	-0.87	-0.86	-0.86	-0.86	-0.85	-0.85	-0.85	-0.85	-0.84	-0.84	-0.84	-0.84
19	-0.96	-0.93	-0.91	-0.90	-0.90	-0.89	-0.89	-0.89	-0.89	-0.89	-0.89	-0.89	-0.89	-0.89	-0.89
18	-0.97	-0.96	-0.95	-0.94	-0.93	-0.93	-0.93	-0.92	-0.92	-0.92	-0.92	-0.92	-0.92	-0.92	-0.92
17	-1.00	-0.99	-0.98	-0.97	-0.96	-0.96	-0.96	-0.96	-0.96	-0.96	-0.96	-0.96	-0.95	-0.95	-0.95
16	-1.01	-1.02	-1.01	-1.01	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-0.99	-0.99	-0.99
15	-1.03	-1.05	-1.05	-1.04	-1.04	-1.04	-1.04	-1.04	-1.04	-1.04	-1.04	-1.04	-1.04	-1.04	-1.04
14	-1.04	-1.08	-1.08	-1.08	-1.08	-1.08	-1.08	-1.08	-1.08	-1.08	-1.08	-1.08	-1.08	-1.08	-1.08
13	-1.06	-1.11	-1.12	-1.12	-1.12	-1.12	-1.12	-1.12	-1.12	-1.12	-1.12	-1.12	-1.12	-1.13	-1.13
12	-1.07	-1.14	-1.15	-1.16	-1.16	-1.16	-1.17	-1.17	-1.17	-1.17	-1.17	-1.17	-1.17	-1.17	-1.17
11	-1.09	-1.17	-1.19	-1.20	-1.20	-1.21	-1.21	-1.21	-1.21	-1.22	-1.22	-1.22	-1.22	-1.22	-1.23
10	-1.10	-1.20	-1.23	-1.24	-1.25	-1.25	-1.26	-1.26	-1.26	-1.27	-1.27	-1.27	-1.28	-1.28	-1.28
9	-1.11	-1.23	-1.27	-1.29	-1.30	-1.30	-1.31	-1.31	-1.32	-1.32	-1.33	-1.33	-1.33	-1.34	-1.34
8	-1.12	-1.26	-1.31	-1.33	-1.35	-1.36	-1.36	-1.36	-1.37	-1.37	-1.39	-1.39	-1.40	-1.40	-1.40
7		-1.29	-1.35	-1.38	-1.40	-1.41	-1.42	-1.43	-1.44	-1.44	-1.45	-1.46	-1.46	-1.47	-1.47
6	-1.13	-1.32	-1.39	-1.43	-1.46	-1.47	-1.48	-1.49	-1.50	-1.51	-1.52	-1.53	-1.54	-1.55	-1.55
5		-1.35	-1.44	-1.49	-1.52	-1.54	-1.55	-1.56	-1.58	-1.59	-1.61	-1.62	-1.63	-1.63	-1.64
4	-1.14	-1.38	-1.49	-1.55	-1.59	-1.61	-1.63	-1.65	-1.67	-1.68	-1.70	-1.71	-1.73	-1.74	-1.75
3		-1.41	-1.54	-1.62	-1.67	-1.70	-1.72	-1.74	-1.77	-1.79	-1.81	-1.83	-1.85	-1.86	-1.87
2	-1.15	-1.44	-1.60	-1.70	-1.76	-1.81	-1.84	-1.86	-1.91	-1.93	-1.96	-1.99	-2.01	-2.03	-2.05
1		-1.47	-1.67	-1.80	-1.89	-1.95	-2.00	-2.04	-2.09	-2.14	-2.18	-2.22	-2.26	-2.29	-2.31
0	-1.16	-1.50	-1.79	-2.03	-2.23	-2.39	-2.53	-2.65	-2.83	-3.03	-3.20	-3.38	-3.54	-3.70	-3.83

Note: When Q_u or Q_L falls between table values, estimate P_u or P_L to the closest 0.10.

The purpose of these cases is to illustrate the importance of providing an accurate and precise produced grading.

The PWL calculations for the individual sieves are completed as discussed previously. The composite PWL is the sum of the individual PWL values divided by the number of sieves evaluated. As expected, Case 1 has the best PWL, with over 99 percent of product within specification. Case 2 shows that if the variability (standard deviation) increases by 50 percent, the composite PWL decreases by 20 percent. With Case 3, the impact of a finer grading with the original standard deviation is a 17 percent decrease in PWL relative to Case 1. Case 4, with the finer grading and increased standard deviation, resulted in the worst PWL of approximately 70 percent.

Table 18.7 PWL Case Studies

Case 1 (Mid-Band gradation with production standard deviation)

Sieve	Lower Limit	Upper Limit	$\bar{X}$	s	QL	QU	PL	PU	PWL
1"	90	100	95	2.1	2.3810	2.3810	100	100	100
3/8"	56	74	65	4.7	1.9149	1.9149	100	100	100
No. 10	32	46	39	3.9	1.7949	1.7949	100	100	100
No. 40	20	28	24	2.6	1.5385	1.5385	100	100	100
No. 200	10	14	12	1.4	1.4286	1.4286	98	98	96
							Composite PWL		**99.2**

Case 2 (Average the same as for Case 1, but standard deviation increased by 50 percent)

Sieve	Lower Limit	Upper Limit	$\bar{X}$	s	QL	QU	PL	PU	PWL
1"	90	100	95	3.2	1.5625	1.5625	100	100	100
3/8"	56	74	65	7.1	1.2676	1.2676	92	92	84
No. 10	32	46	39	5.9	1.1864	1.1864	90	90	80
No. 40	20	28	24	3.9	1.0256	1.0256	84	84	68
No. 200	10	14	12	2.1	0.9524	0.9524	82	82	64
							Composite PWL		**79.2**

Case 3 (Finer gradation throughout)

Sieve	Lower Limit	Upper Limit	$\bar{X}$	s	QL	QU	PL	PU	PWL
1"	90	100	93	2.1	1.4286	3.3333	98	100	98
3/8"	56	74	60	4.7	0.8511	2.9787	85	100	85
No. 10	32	46	35	3.9	0.7692	2.8205	76	100	76
No. 40	20	28	22	2.6	0.7692	2.3077	76	100	76
No. 200	10	14	11	1.4	0.7143	2.1429	74	100	74
							Composite PWL		**81.8**

Case 4 (Finer gradation throughout with standard deviation increased by 50 percent)

Sieve	Lower Limit	Upper Limit	$\bar{X}$	s	QL	QU	PL	PU	PWL
1"	90	100	93	3.2	0.9375	2.1875	81	100	81
3/8"	56	74	60	7.1	0.5634	1.9718	69	100	69
No. 10	32	46	35	5.9	0.5085	1.8644	67	100	67
No. 40	20	28	22	3.9	0.5128	1.5385	67	100	67
No. 200	10	14	11	2.1	0.4762	1.4286	66	98	64
							Composite PWL		**69.6**

18.10 Producer Quality Control

Efforts to achieve quality in the products produced and marketed by an aggregates producer is the business of everyone employed by the producer, and must be a continuing function. Interest in producing and providing quality aggregate cannot be an "on today, off tomorrow" proposition. Lack of quality adversely affects the aggregate producer's business and can result in:

- Loss of business on a project-by-project basis;
- Loss of credibility with user agencies; and
- Loss of an entire market to alternate material types.

Any one of the above losses is undesirable for the aggregates supplier and, therefore, must be avoided if possible.

Aggregates producer personnel should not and must not "see what they can get by with on this job." Rather, they must strive to give the best quality that can be provided on each project within the constraints of the market place such as job requirements, economics, etc.

Aggregates is uniquely different from other materials utilized on a construction project. Because of economic considerations, aggregates are drawn from local resources. Thus, once selection of an aggregates resource has been made by an aggregates producer through proper geological and engineering evaluations, many of the physical and chemical properties of the aggregates produced from a given resource are essentially fixed. Selective mining and special processing procedures can be utilized at some quarries or pits to improve some of these properties, and thereby upgrade the quality of the aggregates. Other properties such as grading can be controlled by the producer.

18.11 Sampling Procedures

In the handling and stockpiling of bulk materials, constant change takes place in the characteristics of the material because of attrition (i.e., wearing down by friction), segregation of sizes, wind erosion and other forces. In order to produce a final product which meets the required specifications, these changes must be identified and the location where they occur determined.

Quality control is only as effective as the data on which it is based. Adequate information about the material being controlled is the key to successful quality control. Sampling is a technique or method for obtaining objective, reliable information about a population. Since it is usually impossible and uneconomical to measure all of the population, the producer or the user or both must be content to select certain samples assuming these parts are representative of the whole population. However, the population from which the sample was taken usually no longer exists. The sample contains only the facts that are available on the subject slice of the population.

Conclusions drawn about the total population from a sample are merely inferences and are subject to verification.

Sampling plans for material acceptance should be agreed upon before project initiation between the contractor/supplier and the owner agency/specifier.

Requirements for Sampling

Two fundamental requirements exist for proper sampling. First, the sample must be taken at random times and locations, utilizing a random sampling plan. Usually samples are taken at various times and during various phases of any cyclic occurrences that exist. Second, all of the material in the material flow stream must be available for sampling. Failure to sample the entire cross section of the material stream results in a partial sample that may not be representative of all the material. When these two fundamental requirements are met, the sample that is obtained should be representative of the material passing the sampling point at the instant the sample was taken. As the sampling size increases, the accuracy of inferences made about all the material becomes greater.[1] Sampling must be performed by responsible and qualified personnel.

Selection of Sampling Points

An aggregates producer is required, by the specifications of his customers, to produce a product of a certain quality, size and gradation. To do so requires many unit operations in which the composition, size and shape of the material are altered. At what point in this sequence of operations should samples of this material be taken? Should it be sampled as it enters the stockpile or bin, as it is being reclaimed and loaded out, or as it is being unloaded at its final destination, or from some other location? How many samples should be taken and how large should they be? There are many different answers to these questions, depending on the desired results.

As aggregate falls into a stockpile or bin, natural forces start changing its character. Gravity tends to move the coarser particles closer to the bottom of the slope. Wind may remove some of the finer particles or bring in and deposit foreign matter that contaminates the product. Rain alters the moisture content of the aggregates. Samples taken from the production stream, or any intermediate location and aggregates stockpiles at random yield some information on the extent of segregation, contamination or other changes that have taken place. This information provides some guidance concerning the need for blending or other corrective action. These samples, however, may not be representative of material that will be shipped at a later time.

Sampling the product as it is loaded into a truck provides data on the properties and gradation of the product going into that particular truck. These samples assure the shipper that the material as loaded out did conform to the buyer's specifications at the time of loading.

Sampling at the unloading point indicates the properties of the material that arrived at the job site. Sampling at the unloading point also yields information about the effect of transportation on the product. Sampling at this point does not give information concerning the size or gradation produced at the plant. *The only reliable method of obtaining a representative sample from a loaded haul unit is by dumping the entire load, mixing it, quartering and splitting it down*.

Random Sampling

Sampling and testing are both important activities that significantly influence the "perception" of the quality of the aggregates being tested. Every precaution must be taken to obtain samples that permit a true estimate of the nature and conditions of the material that they represent. Samples must be obtained using procedures that prevent segregation and minimize sample variation. Further, sampling time and location must be determined on a random, unbiased basis.

Unbiased sampling is achieved only when every element of the material being sampled has an equal chance of being included in the sample. To be entirely unbiased, the element to be sampled must be chosen in advance by use of random procedures, such as random selection by use of random numbers. Randomness does not occur by accident or by lack of direction; it is always the result of a well planned effort.

A truly random sample cannot always be obtained. For example, it is extremely difficult to obtain a sample that represents all the aggregates contained in a stockpile. This difficulty arises because most of the elements are within the stockpile and cannot easily be reached. Nevertheless, sampling efforts must strive for randomness to obtain the most representative sample possible.

Random sampling should be performed in accordance with the American Society for Testing and Materials (ASTM) D3665, Standard Practice for Random Sampling of Construction Materials.[2] This practice covers the determination of random locations or times at which samples can be taken. The procedures set forth in ASTM D3665 eliminate any intentional bias and minimize any unintentional bias on the part of the technician taking the sample.

Sampling Location

There has been much discussion between aggregates suppliers and state agencies as to when and where to sample an aggregates product. The aggregates supplier wants his material to be sampled and tested at his aggregates production plant which is where he has control of the process. He is concerned that changes to the product can occur during transport or at the contractor's worksite, and these changes are beyond his control.

The owner agency wants the aggregates product in place to meet all project specifications. This is where he wants material quality. Quality is what he is paying for and where the "rubber meets the road."

The aggregate supplier does not want to incur a monetary penalty for a quality problem developed by his contractor. Therefore, most aggregates suppliers want aggregates products to be sampled and accepted at the point of production. A quality control plan should be developed and implemented to minimize and control changes that can occur during transport, mixing, placement and compaction of the product.

The most common locations where aggregate samples can be obtained include conveyor belts, bins, stockpiles, trucks, railcars or barges and the roadway after placement. Samples must be properly collected in the field and properly reduced in the laboratory to the necessary testing size. Sampling of aggregates should be conducted following the procedures of ASTM D75, Standard Practice for Sampling Aggregates.[3]

- **Conveyor Belts:** Whenever possible samples should be taken from a conveyor belt. Sampling from a conveyor belt produces a very representative sample of aggregate. However, belt samples are the most difficult to obtain because most producers do not want to stop the conveyor for a sample to be taken. Not only is production lost, but loaded belts may be too heavy to restart and crushers may have to be dug out. Figure 18.5 (see color section) shows sampling from a conveyor belt that is not moving. Automatic sweep-type belt samplers can be utilized to obtain samples without stopping the belt. Automatic samplers increase production costs.

- **Bin Samples:** When samples cannot be taken from a conveyor belt, they should be taken from a holding bin. Obtaining a representative sample from a large holding or storage bin is extremely difficult. Material from the bin should be discharged into a loader bucket and moved to a hard, flat sampling location on the ground. The aggregate should be dumped from the bucket and back-dragged with the bucket to form a circular pile that is 12 to 24 inches in thickness. Samples should then be obtained from the mini-pile using sampling techniques described in Section 18.15.

- **Stockpile Samples:** Sampling from stockpiles should be avoided whenever possible, particularly when the sampling is conducted for the purpose of determining aggregate properties that are dependent upon the grading of the sample. However, samples must be obtained from the material stockpiles when belt or bin sampling is not possible. In reality the vast majority of aggregate samples are obtained from a stockpile. Efforts should be taken to obtain the most representative sample possible, and this requires an understanding of how aggregate segregates as it goes into a stockpile. Most stockpiles are built by discharging aggregate from the end of a conveyor belt. If the conveyor is permanently fixed, a cone-shaped stockpile is formed (See Figure 18.6). If a radial stacker is used, the stockpile will be tent-shaped (See Figure 18.7). Occasionally trucks are used to transport aggregate from bins to build stockpiles. Less frequently, aggregate is dumped over a quarry face to build a stockpile. All these methods cause segregation in varying degrees.

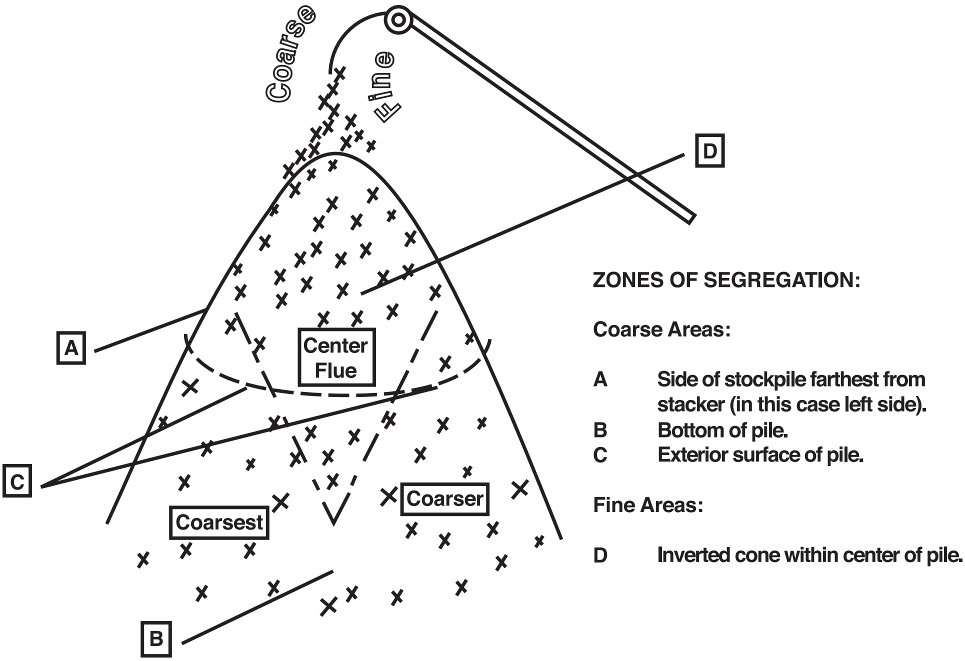

Figure 18.6 Sampling from a Stockpile Formed with a Fixed Conveyor

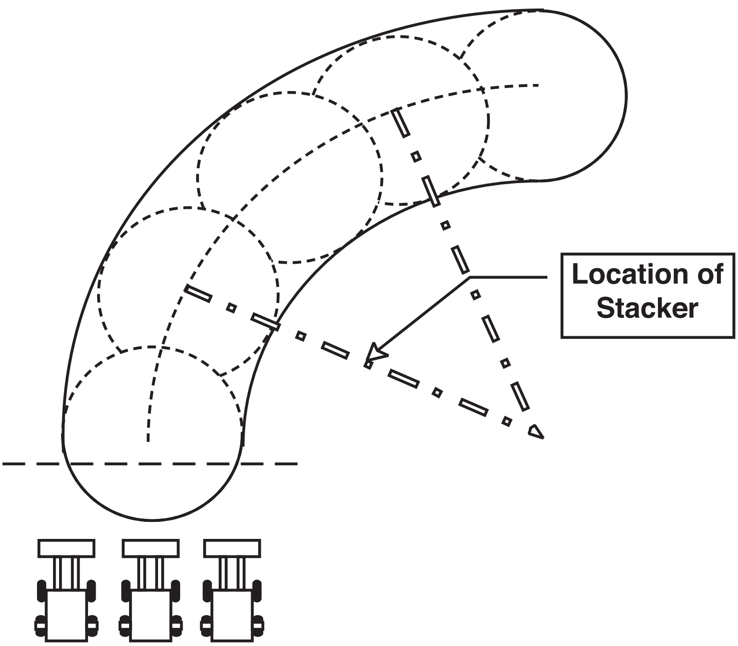

Figure 18.8 Sampling from a Stockpile Formed with a Radial Stacker

Material segregates as it moves on a conveyor belt due to vibration. The fines in the aggregates settle to the bottom of the layer of material being conveyed on the belt as shown in Figure 18.8. As aggregates are discharged off the end of a conveyor belt, the coarser sizes are thrown out and away from the end of the conveyor. The falling aggregates has a tendency to cascade down the side of the stockpile. The fines in the aggregates stay on the belt longer, and drop straight down or toward the underside of the conveyor. The typical aggregates distribution after discharge from a permanent conveyor belt is shown in Figure 18.9. A similar distribution occurs when a radial stacker is utilized. A telescoping radial stacker is shown in Figure 18.10 (see color section). Segregation is influenced by the moisture content of the aggregates, wind conditions and size distribution of aggregates on the belt. The preferred way to get a sample from a stockpile is to use a front-end loader to obtain and remove the material from the stockpile. The loader should move into the stockpile perpendicular to the direction of the stacker as shown in Figure 18.8. The face should be inactive at the time of sampling. Material should be removed from the bottom of the pile and across the entire cross-section of the stockpile. Remove two or more buckets, as necessary, to cause the material from top of pile to cascade down to the bottom; place material into a mini- stockpile; and back-blade the mini-stockpile to approximately a two foot height. Sample the mini-stockpile at several locations and combine material into a composite sample.

Stockpiles constructed by dumping truckloads of aggregates adjacent to each other exhibit minimal segregation. However, aggregates stockpiles constructed by dumping the aggregates over a quarry face generally exhibit excessive segregation. In general, the larger particles move to the outside and to the base of the stockpile.

- **Truck/Rail Car/Barge:** The sampling of aggregates from transport units such as truck, rail car or barge should be avoided whenever possible due to safety concerns and governmental regulations. If a sample from a transport unit is required, the general principles given for sampling from stockpiles should be followed.

- **Roadway:** User agencies frequently obtain samples from the roadway after the aggregates, or aggregates and binder mixture, has been placed and compacted. These samples are taken to assure the agency that the material required by the specifications was actually supplied to the project and is present in the in-place material. Many factors influence the quality of the in-place material including production methods, effect of transportation, construction equipment and practices and climatic conditions. Consequently, the quality of aggregates in the roadway is frequently beyond the control of the aggregates supplier. Samples taken at random from the roadway reflect the extent of segregation, contamination, or other changes that have taken place since production. These changes occur due to multiple handling operations performed by the producer or the contractor or both. The information obtained from roadway samples provides guidance concerning the need for blending of aggregates or other corrective action during the construction operation. These samples may not represent the material shipped from the aggregates production plant to the customer or that may be shipped to the customer at some future time.

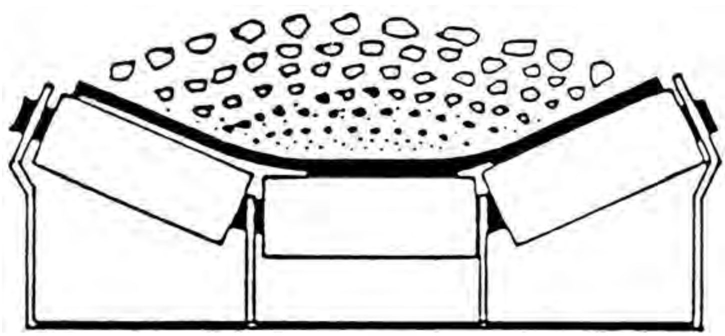

Figure 18.8 Aggregates Segregation on a Moving Conveyor Belt

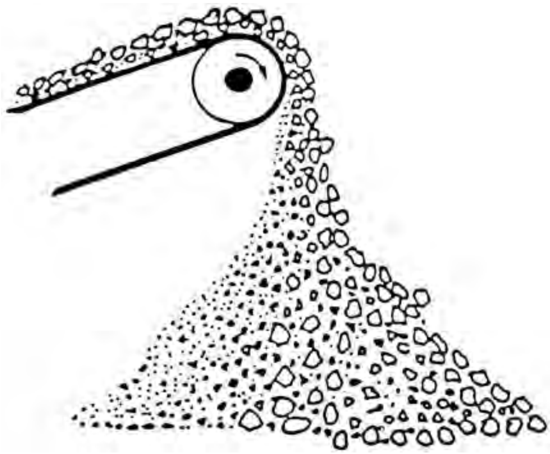

Figure 18.9 Typical Aggregates Distribution from a Fixed Conveyor

Sampling Method

Product testing must be performed on samples of aggregates that are representative of the material being produced. Methods for securing representative samples are as follows:

- **Conveyor Belt Samples.** At least three increments should be taken from the belt and combined into one field sample. The sample should be obtained in the following manner:

  1. Use a sweep type belt sampler, if available;
  2. If a sweep type sampler is not available, stop the conveyor belt prior to taking the sample and lock out the conveyor until completion of the sampling procedure;
  3. With a shovel or scoop separate an area on the belt large enough to provide the proper size sample as discussed later in this chapter. Clear the material ahead of and behind the sample for a distance of at least six inches; and
  4. Carefully scoop all material between the cleared areas into a sample bag, collect the fines on the belt with a brush and add to the sample.

- **Bin Samples.** Bin samples should be taken at random intervals from the bin. The increments are combined to make a single sample. Sample collection is facilitated by discharging the bin into the bucket of a front-end loader and then placing each increment onto a hard, flat surface on the ground. The sample should be taken in the following manner:

  1. The sample should be obtained during the discharge of material from a full or nearly full bin to minimize segregation. In the case of a belt discharge, the conveyor should be operating at normal capacity during normal plant operations.
  2. The sampling device, either a bag or pan, is passed through the entire cross section of the discharge to obtain a representative sample. The speed of the pass is determined by the material being sampled, the size of the sample desired, and the discharge rate.
  3. The sample should not include the initial discharge from a conveyor or newly filled bin.

- **Stockpile Samples.** When a sample must be obtained from a stockpile, the following techniques should be used. Samples should be obtained using a front-end loader as previously described in Section 18.11. When power equipment is not available:

  1. Select the area to be sampled; it should be a minimum distance above the ground of one-third the total height of the material stockpile.
  2. Place a sheet of plywood or a sheet of thin metal, approximately 2 feet by 2 feet, corner first and horizontally into the material directly above the area to be sampled to a depth of at least 1 foot. The sample is obtained from the stockpile directly below the sheet of plywood or metal.
  3. Discard material to a depth of approximately 6 inches by removing it with a shovel. Sample the material until a sufficient amount is obtained as discussed later in this chapter.

- **Truck/Rail Car/Barge Samples.** General principles for sampling aggregates from stockpiles are applicable to sampling from trucks, rail cars, barges or other transportation units.

- **Roadway Samples.** Samples obtained from the roadway should be selected by a random method such as that set forth in ASTM D3665, Standard Practice for Random Sampling of Construction Materials. A minimum of three equal increments, selected at random, should be taken and combined to form the required field sample. All increments should be taken for the full depth of the material, and care should be exercised to exclude any underlying material from becoming part of the sample.

Size of Sample

Sufficient material must be obtained and submitted to the testing laboratory to permit proper execution of all desired tests. The quantities given in Table 18.8 generally provide adequate material for routine grading and quality analysis. A "rule of thumb" for sample size is to obtain a 50-pound sample for each inch of diameter of the coarsest particle. A sample which is too large can be reduced in the laboratory, but a sample which is too small is of no value and represents wasted effort.[5]

Table 18.8 Required Size of Samples

Maximum Normal Size of Aggregates*		Approximate Minimum Mass of Field Samples, lb (kg)**	
Fine Aggregates			
No. 8	(2.36 mm)	25	(10)
No. 4	(4.75 mm)	25	(10)
Coarse Aggregates			
⅜ in.	(9.5 mm)	25	(10)
½ in.	(12.5 mm)	35	(15)
¾ in.	(19.0 mm)	55	(25)
1 in.	(25.0 mm)	110	(50)
1 ½ in.	(37.5 mm)	165	(75)
2 in.	(50 mm)	220	(100)
2 ½ in.	(63 mm)	275	(125)
3 in.	(75 mm)	330	(150)
3 ½ in.	(90 mm)	385	(175)

* *For processed aggregates the maximum nominal size of particles is the largest sieve size listed in the applicable specification upon which any material is permitted to be retained.*

** *For combined coarse and fine aggregates (for example, base or subbase), minimum weight shall be coarse aggregates minimum plus 25 lb (10 kg). (After ASTM D75, Standard Practice for Sampling Aggregates[3])*

Aggregates samples obtained in the field should be placed in sample containers or sample bags that are constructed to preclude loss or contamination of any part of the sample. Sample bags also should be made of a durable material that does not deteriorate upon exposure to sunlight or rain. Further, the containers or bags should be sufficiently rigid to prevent damage or degradation of the aggregates due to mishandling during shipment.

Labeling and Identification

Proper labeling and identification of each sample is as important as sampling and testing activities. However, this important task is often overlooked or ignored. Every sample obtained for test should be identified with the following basic information:

- Sample identification
- Material identification
- Project identification
- Sampling date and time
- Sample location
- Sampled by
- Tests to be performed
- Other pertinent information

Two cards containing the above information should be prepared for each sample using waterproof ink. The cards should be made from a water-resistant material that does not easily fade, run or tear in the presence of moisture. One card should be placed inside the sample container or bag. The second card should be placed on a string or wire used to tie the sample bag or it should be permanently affixed to the exterior surface of the sample container.[6] Transmittal of the information on a separate form is not an acceptable alternative, unless the separate form duplicates information on an attached label.

Types of Samplers

Samples can be obtained by manual sampling procedures or automatic sampling equipment. Manual sampling procedures are performed by a technician who physically obtains a field sample manually. The technician either stops a belt and shovels material from the belt into an appropriate container, discharges material from a bin and shovels material from this sample stockpile into an appropriate container, or digs into a stockpile, truck load or rail car load and shovels material into an appropriate container.

Automatic sampling is accomplished without major physical activity on the part of the technician conducting the sampling. Three types of automatic samplers frequently utilized in the aggregates industry are:

1. Sweep-type conveyor belt sampler
2. Automatic belt discharge sampler
3. Chute sampler

The *sweep-type conveyor belt sampler* is a rotating device that is positioned over a moving conveyor or belt as shown in Figure 18.11. The direction of rotation is perpendicular to the direction of material flow. When activated the device rotates through a full 360º circle and sweeps material off the belt into a discharge chute. The sampler is either manually activated or automatically activated by a signal from a control system.

The *automatic belt-discharge sampler* is a straight-line sampler as shown in Figure 18.12. The sample cutter obtains a representative sample by moving at a constant speed through the falling stream of aggregates as the aggregates comes off the end of a conveyor belt. The sampler may be operated either continuously or intermittently.

The *chute sampler* is designed to sample material handled in chutes or pipes. The unit consists of an automatic sampler mechanism, sample cutter and steel housing as illustrated in Figure 18.13.

Use of automatic sampling equipment saves many hours of costly operator time while producing reliable and representative samples. However, a limit exists to the amount of money that an aggregates producer can spend for sampling equipment. Consequently, such automatic sampling equipment is normally found only on high production volume plants. As aggregates specifications for specific end-use applications become more exacting, greater utilization will be made by producers of automatic sampling equipment. In most cases the investment in automatic samplers is a small fraction of what is expended for sampling, testing and analysis.

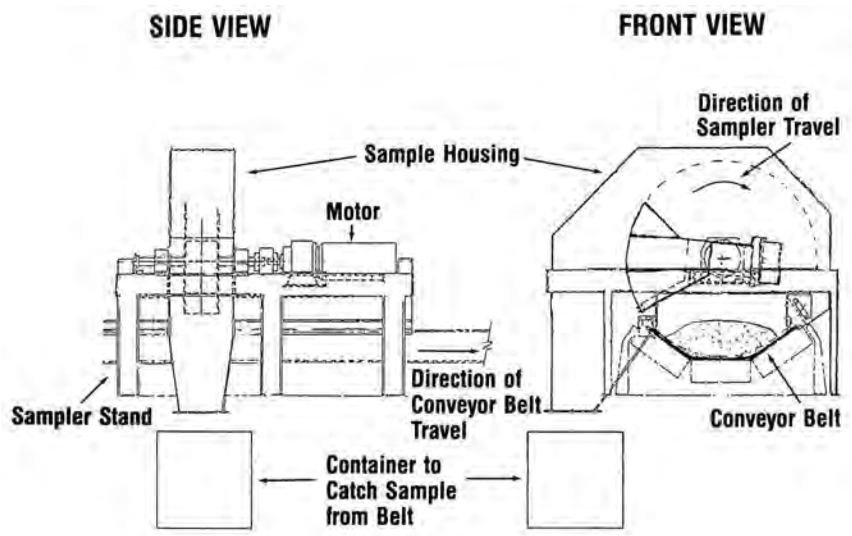

Figure 18.11 Sweep-type Conveyor Belt Sampler

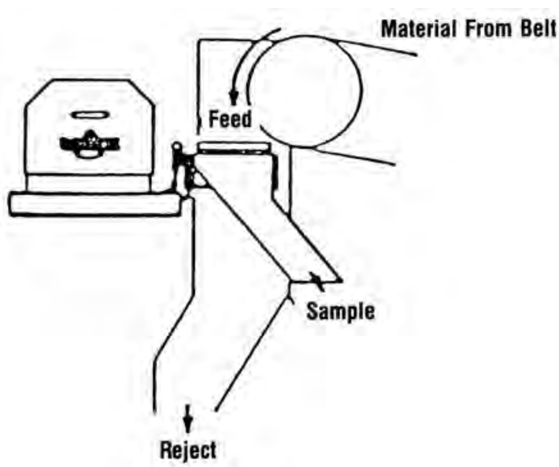

Figure 18.12 Automatic Belt-discharge Sampler

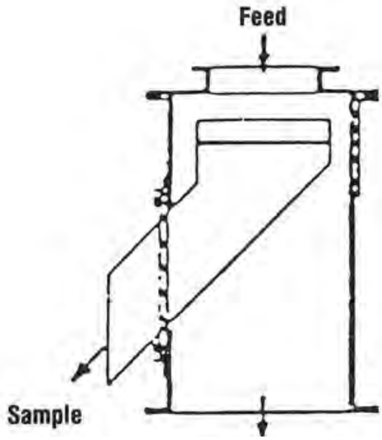

Figure 18.13 Chute Sampler

Sample Preparation

Sample preparation includes a series of procedures applied to the total field sample for the purpose of obtaining one or more representative subsamples for testing. Preparation procedures include a combination of several of the following tasks: sample reduction, air drying, oven drying, crushing, grinding or pulverizing, screening and mixing. Each task that is performed must be accomplished without changing the quality characteristic to be measured.

- **Reduction of Field Samples.** After field sampling, the samples are reduced to testing size by proper splitting in accordance with procedures given in ASTM C702, Standard Practice for Reducing Field Samples of Aggregates to Testing Size.[7] A field sample of aggregates are reduced to test sample size by using a mechanical splitter for coarse aggregates, a different mechanical splitter for fine aggregates or by quartering.

- **Core Samples.** Core samples are frequently obtained by the aggregates producer to permit evaluation of the physical and chemical properties of stone. Once the core zones are crushed, sampling procedures previously described for production samples (belt, bin, stockpile, etc.) should be followed to ensure that representative test samples are prepared for subsequent testing.

Testing Frequency

The quality of a material as defined by a particular characteristic such as aggregates gradation is a frequency distribution function. Quality cannot be accurately represented by a single value. The variability in a group of observed values of a particular quality characteristic is made up of three parts: variability of the material itself, errors in sampling and errors resulting from the testing. In some practical problems the error of measurement (sampling and testing) may be large compared with the variability of the material; in others, the converse may be true.

Because of the variability encountered with all engineering materials, establishing through testing the true value of a measured quality characteristic is difficult. If only one test measurement is made, the precision of the measurement cannot be determined unless data are available that were obtained previously from similar tests on similar materials. If two measurements are made, although the two results will undoubtedly differ, some indication is obtained of the variation to be expected. If more than two measurements are made, the average of the measurements usually provides a better estimate of the true value of the characteristic being measured. If a sufficient number of measurements are performed, statistics can be used to describe the reliability of the measurements. The probability also can be determined with a given degree of confidence that the true value of the characteristic being measured is included within any specified range (maximum allowable error) above or below the average.

18.12 Analysis of Test Data

Through the sampling and testing process, test data are produced from which quality control decisions are made. Results of tests performed on samples of the same material differ from one another because of material variability and testing error. Knowledge of the source and magnitude of variability and the source and magnitude of testing error is essential to correct data analysis and to subsequent decisions concerning material quality.

Test results are subject to variations in the properties of the material being tested, and to discrepancies in the testing methods and procedures resulting from different testing operators within a given laboratory or to different testing laboratories. The following sections briefly focus on discrepancies in testing methods and procedures.

Single Operator Precision

Single-operator precision provides an estimate of the difference in test results that exists between repeated measurements made on the *same* material in the same laboratory by the *same* operator using the same testing equipment within a span of a few days. Information provided in each ASTM Standard Test Method indicates the single-operator precision of the method. The results of two properly conducted tests by the same operator should not differ by more than the single-operator precision value. If greater differences are observed, the testing methods, procedures or equipment is suspect.[8]

Between Laboratory Precision

Between laboratory precision provides an estimate of the difference in test results that exists between measurements made on the *same* material in two or more different testing laboratories. Each ASTM Standard Test Method gives the between laboratory precision of the test method. The results of two properly conducted tests by two different laboratories should not differ by more than the between laboratory precision value. If greater differences are observed, the testing methods, procedures, or equipment of one (or both) of the laboratories is suspect.[8]

95 Percent Confidence Interval

A *confidence interval* is a range around the mean test value within which test data fall with a specified degree of confidence. For example, consider a particular test which is performed 100 times. Ninety-five out of the 100 test results fall within a certain band about the mean while only five fall outside of the band. Then the band is by definition the 95 percent confidence interval. Confidence limits of 99 percent and 99.9 percent include 99 out of 100 and 999 out of 1000 measurements, respectively.[9]

Applied statistics provide techniques for the calculation of the confidence intervals for a given test parameter from a limited number of measurements. In the aggregates industry the 95 percent confidence interval is frequently utilized in the analysis of data and for decision-making. However, when the consequences of a wrong decision are severe, the 99 percent or the 99.9 percent confidence limits should be utilized.

18.13 Quality Assurance Programs Used for Aggregates

Statistically based specifications have been used in quality assurance programs with a strong dependence on statistical analysis since the 1970s. As these programs were being developed, there was recognition of the need for separate quality process control and for acceptance functions. The contractor, or aggregates producer, is in the best position to conduct the process control function because it depends on the contractor or producer's personnel and equipment. The acceptance function is performed to ensure that satisfactory quality control has been exercised and that a proper degree of compliance to the specifications has been attained. This function has been deemed an owner agency function.

Quality control and acceptance programs used for aggregates base and subbase products tend to be similar to those for other processed materials.[14] Some agencies use statistically based specifications, and others tend to use materials and methods provisions in their programs. The forms and ingredients of quality assurance programs vary appreciably from agency to agency, and can be seen in the responses of a survey of state highway agencies reported in 2005.[14] This survey indicated that all agencies do not have identical acceptance practices. Responses from 45 agencies were reported. These responses indicated:

- 15 use materials and methods provisions.
- 14 use QA programs with the owner agency controlling quality and performing acceptance.
- 21 use quality programs with the contractor controlling quality and the owner agency performing acceptance.
- 10 use quality assurance programs with the contractor controlling the quality and the owner agency using contractor test results in the acceptance decision.

18.14 Properties Used for QC and Acceptance

The properties used for quality control and acceptance of aggregates base and subbase materials include:

	Used by DOT for QC	Used by DOT for QA
Compaction	20	45
Moisture content	14	24
Gradation	27	42
Aggregates fractured faces	9	21
Atterberg limits	1	6
L.A. degradation	0	4
Thickness	0	4
Sand equivalence	0	3
R-value	0	3

Thirty five of the 45 responding agencies use an accept/reject acceptance plan. Sixteen use a pay adjustment system. Eight of the 16 use a stepped pay schedule, four use equations and four use other procedures.[14]

18.15 Quality Measures Used for Acceptance

The quality measures used by owner agencies for acceptance of aggregates base and subbase materials include the following:

	No. of Agencies
Individual values	25
Percent within limits	13
Range	13
Average	7
Standard deviation	3
Average absolute deviation	1
Conformal index (W.Va.)	1

The total number of quality measures exceeds the number of survey responses of 45 because some agencies use more than one quality measure.[14]

18.16 Use of Contractor's Test Results for Acceptance

Many individuals, including most contractors and aggregates suppliers, believe that quality control test data determined by the contractor or aggregates supplier, or both should be used in the acceptance decision. Can or should the contractor's or aggregates producer's test results be used in the acceptance decision? There is significant duplication of testing and expense and manpower required when both the supplier/contractor and an owner agency perform testing on aggregates materials being used for a given project. During the 1980s and early 1990s, federal regulation did not permit use of contractor's/supplier's test results in the acceptance procedure. However, the contractor/supplier's test results could be used on state-funded construction at that time.

In 1995, the FHWA recommended that contractor sampling and testing be used in the acceptance decision. This recommendation was implemented with the adoption of 23 CFR 637. This regulation enables transportation agencies to incorporate contractor test data into their acceptance procedures provided adequate checks and balances are in place to protect the public investment.[14] Use of contractor/supplier data is permitted when the technician performing the testing has adequate training in correct test methods and standard procedures and has been certified to perform the testing.

Adoption of 23 CFR 637 affected the diversity of quality assurance programs in the fifty states because the rule provides flexibility to the owner agency and imposes important requirements for contractor/supplier obtained test results to be used. These requirements include:

1. Assurance that qualified laboratories and personnel are used for sampling and testing,
2. Assurance that the equipment and personnel are capable of performing the tests properly,
3. Assurance, by independent assurance testing, that the testers and equipment remain capable of performing the tests properly, and
4. Assurance that the product is of the desired quality by verification sampling and testing.

Consequently, there are three integral parts for an effective quality assurance program: quality control during the production process, quality acceptance during or after production and independent assurance. Verification testing by an independent assurance program is used to validate the quality of the material. Independent assurance involves a separate and distinct schedule of sampling, testing, and observation than that used for process control and for quality acceptance testing. Administration of the independent assurance system varies appreciably among state highway agencies.[14]

18.17 Sources of Variability in Test Data

The variability in an aggregates product is rarely known, nor is it constant. Differences in two test results are obtained from three sources: differences in the material, differences in testing procedure and differences in sampling procedures. Variability in a product produced by a given process is due to *chance causes* and *assignable causes*. *Chance causes* of variation are too small to be economically identified or corrected. *Assignable causes*, on the other hand, are large in comparison to the total process variation. Consequently, identification and correction of assignable causes and reduction in product variability due to such causes are economically worthwhile.

Some variability in production is unavoidable. The amount of variability depends on various characteristics of the production process such as the equipment, materials and operators. Where both upper and lower values are specified for a quality characteristic, an important question is whether the variability of the process is so great that it is impossible to make all the product within the specification limits.

Using *independent samples* for process control, material acceptance and independent verification ensures that all sources of differences are measured and considered in the acceptance decision. Frequently, *split samples* are taken to resolve quality disputes. Split samples only address differences in testing procedures and should be used only to provide assurance that the contractor or supplier or the owner agency, or both are performing the test properly. The testing variability between contractor/supplier and agency test results must be kept to a minimum.

18.18 Risk

One or more test results are used to make a decision of acceptability of the aggregates product being produced. This decision involves a certain amount of *risk* that a wrong decision will be made. Two basic risks are producer/supplier and owner agency.

Producer/supplier risk is the risk of rejecting "good" material. Owner agency risk is the risk of accepting "bad" material. Obviously, the goal is to minimize the risk to both the producer/supplier and the owner agency. Figure 18.14 shows the two types of risk.

Specification tolerances and number of test results used influence the risk involved for both the contractor/supplier and the owner agency. When an acceptance decision is based on a single sample, the owner agency's risk is high and the contractor/supplier's risk is low. The only way to decrease the owner agency's risk is to increase the contractor/supplier's risk. Further, the only way to reduce both types of risk is to increase the number of samples thereby increasing the size of the data base.

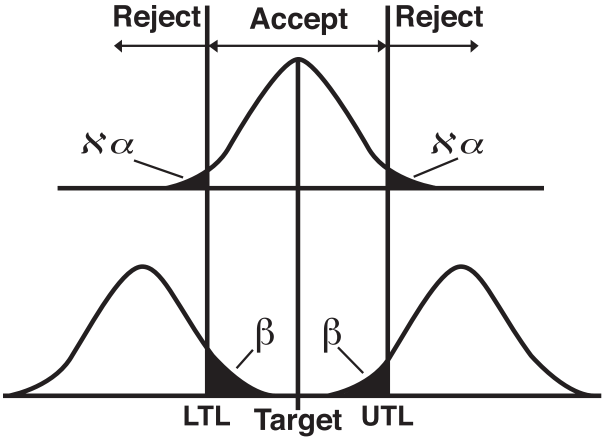

Figure 18.14 Producer/Supplier and Owner/Agency Risk

18.19 Verification of Independently Obtained Test Data

Two procedures are used for verification of independently obtained test results. The procedures most frequently used are the *F-test* and the *t-test*. These procedures usually are used together. The procedures involve two hypothesis tests, where the null hypothesis for each test is that the contractor/supplier's test and the agency's test are from the same population. The null hypotheses are that the variabilities of the two data sets are equal for the *F-test* and that the means of the two data sets are equal for the *t-test*. Both the means and the variances should be compared when comparing two sets of data. The combination of the F-test and the t-test is more statistically sound and has more power to detect actual differences than a method using a single test result.[14]

F-Test

The F-test is a method for comparing variability by comparing variances of two sets of data. It is based on the ratio of the variances of the data sets. The test is conducted at a selected level of significance, typically 0.05 or 0.01. The variance (standard deviation squared) of the QC tests (contractor/supplier test data) is calculated. The variance of the QA tests (owner agency test data) is then calculated. The value F is calculated as the ratio of the two variances, always using the larger of the two variances in the numerator. A critical F value for the selected level of significance is determined from Table 18.9. The degrees of freedom associated with each data set, which is one less than the number of test values in the data set is needed. If the calculated F value is greater than or equal to the critical F value, the two data sets have significantly different variabilities. If the calculated F value is less than the critical F value, there is no reason to believe the two variabilities are significantly different.[13]

Table 18.9 Critical F Values

Degrees of Freedom for Denominator	Degrees of Freedom for Numerator											
	1	2	3	4	5	6	7	8	9	10	11	12
1	16200	2000	21600	22500	23100	23400	23700	23900	24100	24200	24300	24400
2	198	199	199	199	199	199	199	199	199	199	199	199
3	167	149	141	137	135	133	132	131	130	129	129	128
4	31.3	26.3	24.3	23.2	22.5	22.0	21.6	21.4	21.1	21.0	20.8	20.7
5	22.8	18.3	16.5	15.6	14.9	14.5	14.2	14.0	13.8	13.6	13.5	13.4
6	18.6	14.5	12.9	12.0	11.5	11.1	10.8	10.6	10.4	10.2	10.1	10.0
7	16.2	12.4	10.9	10.0	9.52	9.16	8.89	8.68	8.51	8.38	8.27	8.18
8	14.7	11.00	9.60	8.81	8.30	7.95	7.69	7.50	7.34	7.21	7.10	7.01
9	13.6	10.10	8.72	7.96	7.47	7.13	69.88	6.69	6.54	6.42	6.31	6.23
10	12.8	9.43	8.08	7.34	6.87	6.54	6.30	6.12	5.70	5.85	5.75	5.66
11	12.2	8.91	7.60	6.88	6.42	6.10	5.86	5.68	5.54	5.42	5.32	5.24
12	11.8	8.51	7.23	6.52	6.07	5.67	5.52	5.35	5.20	5.09	4.99	4.91
15	10.8	7.70	6.48	5.80	5.37	5.07	4.85	4.67	4.54	4.42	4.33	4.25
20	9.94	6.99	5.82	5.17	4.76	4.47	4.26	4.09	3.96	3.85	3.76	3.68
24	9.55	6.66	5.52	4.89	4.49	4.20	3.99	3.83	3.69	3.59	3.50	3.42
30	9.18	6.35	5.24	4.62	4.23	3.95	3.74	3.58	3.45	3.34	3.25	3.18
40	8.83	6.07	4.98	4.37	3.99	3.71	3.51	3.35	3.22	3.12	3.03	2.95
60	8.49	5.80	4.73	4.14	3.76	3.49	3.29	3.13	3.01	2.90	2.82	2.74
120	8.18	5.54	4.50	3.92	3.55	3.28	3.09	2.93	2.81	2.71	2.62	2.54
∞	7.88	5.30	4.28	3.72	3.35	3.09	2.90	2.74	2.62	2.52	2.43	2.36

**Note: This is for a two-tailed test. Level of Significance, $\alpha = 0.01$*.*

t-Test

The t-test is a comparison of the means of two data sets. the test is conducted at a selected level of significance, typically 0.05 or 0.01. The t-test determines whether the means of the two data sets differ from one another or can be assumed to be equal and came from the same population. The mean of the QC tests (contractor/supplier test data) is calculated. The mean of the QA tests (owner agency test data) is then calculated.

If the variances of the two data sets are determined to be different, the t-test is conducted using individual sample variances and individual sample sizes. The t-value is computed and compared to a critical t-value obtained from Table 18.10.

If the variances are determined to be equal, the t-test is conducted using a pooled estimate for the variance (weighted average) and a pooled degrees of freedom. The t-value is computed and compared to a critical t-value obtained from Table 18.10.

When the computed t-value is less than the critical t-value there is no reason to believe that the means of the two data sets are significantly different. When the computed t-value is greater than or equal to the critical t-value, the two data sets have significantly different means.[13]

Table 18.10 Critical t Values

degrees of freedom	α = 0.01	α = 0.05	α = 0.10
1	63.657	12.706	6.314
2	9.925	4.303	2.920
3	5.841	3.182	2.353
4	4.604	0.776	2.132
5	4.032	2.571	2.015
6	3.707	2.447	1.943
7	3.499	2.365	1.895
8	3.355	2.306	1.860
9	3.250	2.262	1.833
10	3.169	2.228	1.812
11	3.106	2.201	1.796
12	3.055	2.179	1.782
13	3.012	2.160	1.771
14	2.977	2.145	1.761
15	2.947	2.131	1.753
16	2.921	2.120	1.475
17	2.898	2.110	1.740
18	2.878	2.101	1.734
19	2.861	2.093	1.729
20	2.845	2.086	1.725
21	2.831	2.080	1.721
22	2.819	2.074	1.717
23	2.807	2.069	1.714
24	2.797	2.064	1.711
25	2.787	2.060	1.708
26	2.779	2.056	1.706
27	2.771	2.052	1.703
28	2.763	2.048	1.701
29	2.756	2.045	1.699
30	2.750	2.042	1.697
40	2.704	2.021	1.684
60	2.660	2.000	1.671
120	2.617	1.980	1.658
∞	2.576	1.960	1.645

Note: This is for a two-tailed test.

18.20 Verification of Split Sample Values

There are two procedures frequently used for comparing split samples: D2S limits and the paired *t-test*.

D2S Limits

The D2S limit indicates the maximum acceptable difference between two test results obtained on test portions of split samples of the same material. The limit can be determined for both single and multi-laboratory testing. The limit represents the difference between two individual test results that has approximately 5 percent chance of being exceeded if the tests results are actually from the same population. The value determined by this procedure is contained in many AASHTO and ASTM standard test methods.[14]

If the test difference is less than or equal to the D2S limit, the contractor/supplier test result is verified. If the test difference exceeds the D2S limit, the contractor/supplier test result is not verified and the cause of the difference must be investigated.

Paired t-test

When more than one pair of split sample test results are to be compared; the paired t-test is used. Differences between pairs of tests are used to determine whether the average difference is statistically different from zero. The difference within pairs, not between pairs is tested. The t-statistic is calculated by use of Equation 18-9.

$$t = Xd /(sd/ n) \qquad (18\text{-}9)$$

where

Xd = the average difference between the split sample test results
sd = standard deviation of the differences between split sample test results
n = number of split sample differences.

The calculated t-value is compared with the critical, value and tcrit obtained from a table of t-values.[14]

18.21 Payment Adjustment Systems

Effective payment schedules encourage contractors and aggregates suppliers to apply appropriate quality control practices to ensure that the finished product will equal or exceed the specified level of quality a high percentage of the time. Payment adjustment is used in lieu of removal of product because it did not meet the specifications. Use of both incentive payment factors and disincentive payment factors is relatively common today. Incentive payment clauses permit payment of incentives for product that is exceptionally better than required by the specifications. Benefits of incentive pay are improved quality, positive psychological affect for being rewarded for excellent control and fairness to the contractor/ supplier.[14]

Disincentive pay is received by a contractor when the product used in the construction does not meet applicable specifications. The payment schedule provides payment commensurate with the quality actually provided. The primary purpose of a payment schedule is to obtain high quality material in the project, thereby reducing future costs due to poor quality construction. A secondary purpose is to allow the owner agency to recoup at least part of the anticipated future costs that may result from use of the poor quality material. Reduction in pay may range from 50 to 100 percent of the in-place cost of the product, depending on the degree on nonconformance.

A contractor may receive a reduced payment due to several aggregates related factors. Most common factors relate to gradation and amount of minus No. 200 fines in the product. A high *plasticity index* (PI) in an aggregates base material and coatings on aggregates for asphalt or concrete mixtures are also causes for receiving disincentive pay.

When a contractor is faced with a penalty payment due to an aggregates related problem, he normally seeks reimbursement for his total monetary loss from his aggregates supplier. This cost can be very significant, and can easily exceed the total cost of the aggregates product that was shipped to the project.

Step pay factors or equations are used in pay adjustment schedules. A typical stepped payment schedule based on PWL is shown in Figure 18.15. There has been an increasing trend to use continuous (equation-type) payment schedules, also shown in Figure 18.15. The equation for this continuous schedule is given in Equation 18-10.

$$PF = 55 + 0.5\ PWL \quad (18\text{-}10)$$

where

PF = payment as a percent of unit bid price
PWL = estimated percent within limits

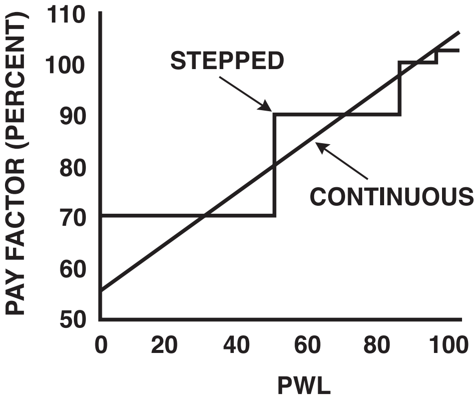

Figure 18.15 Payment Schedules Based on PWL

There is a distinct advantage to use of the continuous form of payment schedule. Continuous payment schedules provide a smooth progression of payment as the quality attribute varies. There are two or more boundaries in a stepped payment schedule, and the quality estimate for a sample may fall close to and on one side or the other of the boundary. Substantial differences in payment level could be realized by the contractor, which may lead to disputes with the owner agency.

18.22 Factors Influencing Minimum Testing Frequency

This section considers the complex subject of testing frequency and sets forth considerations that must be made to establish a testing frequency for each product at each aggregates production plant. Testing frequency should not be a constant per unit volume of production at all plants and for all products. The desired testing frequency is influenced by the following factors:

1. Average percent passing a given sieve relative to specification limits for that sieve;
2. Product variability as expressed by the standard deviation (s);
3. Accuracy desired in the average calculated for the sample;
4. Use of an individual test result for production control (immediacy of data use);
5. Use of data for indicating ability to comply with specifications (historical summarization); and
6. Economics involved in production of product not conforming to specifications. The action taken if an out-of-specification product is produced may be to reprocess it or ship it anyway.

Process conditions may change due to assignable causes with resulting variability in product gradation. As a result a testing frequency cannot be established that will, in itself, provide a 95 percent confidence that the material supplier is producing a specification product. If the production process is constant and if the samples taken for test all represent the same population, then the target gradation is a constant for a given product. For this condition a minimum testing frequency can be established that permits accurate characterization of the material produced. Unfortunately, in the aggregates production process many factors interact and continuously affect production conditions, including changes in:

1. Parent material geology;
2. Moisture as influenced by weather;
3. Tonnage through plant;
4. Plant maintenance;
5. Production of excess aggregates sizes; and
6. Demand for specific aggregates sizes.

As a result, producers do not attempt to produce each product to a single target gradation. Rather, a product is usually produced that is within a master grading band which meets the specifications for the product. As long as the average gradation established for a given time period is within the master band, everything is considered to be correct. Little or no significance is given to producing the same product to another average gradation within the master band during another time period. In reality, two different products have been produced, even though both are in the same master grading band and are identified by the same product code or product name.

18.23 Considerations for Establishing Testing Frequency

The following considerations should be made for establishing testing frequency for each product at a given plant:

1. The testing frequency must equal or exceed the minimum established by the state transportation agency or the specifying organization.

2. A minimum of nine samples is required to calculate a valid estimate of the standard deviation for a given time period or production quantity.

3. Minimum testing frequency should be established for each operation and for each product produced. When historical data indicate the average gradation is in a statistically acceptable zone for the control sieve, i.e., between upper and lower danger limits, the minimum sampling frequency can be established by the procedure presented in Section 18.5. Before this procedure can be used, the magnitude of error must be established that can be accepted between the "average established from the sample" and the "true average" of the product being produced. For example, if the true average amount passing is 48 percent and a maximum allowable error of 1 percent is accepted, then the minimum sample size required for a product that has a known variability can be calculated. With this minimum sample size, one can be 95

percent confident that the average gradation value established from the sample is within the range created by the true average plus or minus the maximum allowable error, which for this example is 47 to 49 percent. To use the procedure, the assumption is made that all data come from the same population and are representative of the product being produced. If this is not the case, a greater number of samples are required.

Consider the situation where the average percent passing value is in a statistically acceptable zone, but the estimate of the standard deviation is greater than 4 percent. Action should be taken to establish the cause of the high estimate of standard deviation and to reduce this value, if possible, by better production control. One of two situations may exist. First, the data may represent one population (no change in plant setup, production process, etc.). This condition indicates a highly variable product with no assignable cause(s) for the high variation. A very high sampling frequency is required for determination of good and bad product, and to direct product use accordingly. All the testing required to properly characterize such a product probably cannot be performed because of economics and inspector time requirements. Consequently, the decision should be made to test as frequently as possible, within present operating constraints.

The second situation is one where the average percent passing value of the product is knowingly changed either to maximize production of another high demand product or to reduce inventory of a surplus product. However, the two products that are produced are within a common master gradation band and distinction between them is not made. An example is periodically adding excess No. 7 size stone into the No. 57 size product. In essence two different No. 57 products are produced and each should be considered separately. Two different populations exist, depending on when the excess No. 7s are added to the product. Testing frequency must be established for each subproduct rather than for the No. 57 product as a whole, unless both subproducts are placed into a common stockpile.

4. Another consideration relates to the action taken, if any, if a single test result suggests that the process is out of control. Test results can be used to control production, or simply to develop a historical representation of the product at the location and time it is tested. If the results are used for production control, then economics related to production of unacceptable material must be considered. When costs of unacceptable material are high, testing frequency must be increased to minimize the production of large quantities of product between tests. Unexpected process changes may occur at any time in the aggregate production process. Consequently, testing of critical products must be performed more frequently than testing of noncritical products. Noncritical products are defined as products that have low production cost and low replacement cost in the event they are rejected from use.

18.24 Establishing Conformance with Specification Requirements

To establish conformance with a specification requirement, one must determine statistically valid, recent values for the average ($\bar{X}$) and estimate of standard deviation(s) for the product being produced. In the event that the number of tests performed during the monthly period is not sufficient to permit calculation of statistically valid parameters, additional testing should be performed. Once values of $\bar{x}$ and s are obtained, analysis of the production process can be initiated following the steps given below:

Step 1. First, establish the control sieve (or sieves) for the product being evaluated. The control sieve is a sieve for which a specification requirement exists and for which an upper and a lower limit other than zero or 100 also exists. Normally the specification requirement for the control sieve encompasses the 50 percent passing value, such as 40 to 70 percent or 25 to 60 percent. Occasionally, sieves with specification requirements of 10 to 30 percent or 90 to 100 percent are selected as the control sieve for the particular product.

Step 2. Determine the upper and lower specification limits for the control sieve. The range of the specification limits is established by subtracting the lower specification limit value from the upper specification limit value. If, for example, the specification limits for the control sieve are 25 to 60 percent passing, the range of the specification limits (R) is 35 percent.

Step 3. Calculate a parameter termed the Ratio, which is defined as the ratio of the range (R) in the specification limits for the control sieve to the estimate of the standard deviation established for the control sieve. If the estimate of the standard deviation is established to be 4 percent, then for the previous example the Ratio equals 35/4 =8.75.

Step 4. Determine the *probability of nonconformance level* (PNL) acceptable for the product. The PNL gives the percentage of all possible test results which will fall outside of the specification limits. As the PNL increases, the producer assumes a greater risk (i.e., a higher probability) of nonconformance of the product with specification requirements. For aggregates production processes, either a 5 or a 10 percent probability of nonconformance level should be selected by the producer. Only in unusual circumstances should the accepted probability of nonconformance level exceed 10 percent. For the example being considered, assume a probability of nonconformance level of 5 percent.

Step 5. Determine the "Factor" to use in establishing upper and lower danger limits for the established probability of nonconformance level using information contained in Table 18.11 or Table 18.12. For this example, the Factor is 1.64.

Table 18.11 Factor to use when "Ratio" is Greater than or Equal to Six

Maximum Acceptable Probability of Nonconformance with Specification	Factor
2.5	1.96
5.0	1.64
7.5	1.44
10.0	1.28
15.0	1.04

Table 18.12 Factor to Use When "Ratio" is Less than Six

Maximum Acceptable Probability of Nonconformance with Specification	Factor
2.5	2.24
5.0	1.95
7.5	1.78
10.0	1.64
15.0	1.44

Step 6. Calculate the upper and lower danger limits. the upper danger limit (UDL) is determined by subtracting the product of the Factor times the estimate of the standard deviation (s) from the upper specification limit value:

$$\text{UDL} = \text{Upper Spec Limit} - (\text{Factor})\ (\text{Estimate of s}) \tag{18-11}$$

For the example, UDL equals 60 - 1.64(4) = 53.4%.

The lower danger limit (LDL) is determined by adding the product of the Factor times the estimate of the standard deviation (s) to the lower specification limit value:

$$\text{LDL} = \text{Lower Spec Limit} + (\text{Factor})\ (\text{Estimate of s}) \tag{18-12}$$

For the example, LDL equals 25 + 1.64(4) = 31.6%.

Step 7. Plot the upper and lower specification limits for the control sieve, the Upper and Lower Danger Limits, and the average percent passing value for the control sieve on a performance chart as illustrated in Figure 18.16.

The zone that exists (if any) between the UDL and the LDL is the Acceptance Zone. If the average percent passing value for the given sieve lies within the Acceptance Zone, aggregates is being produced that has equal to or less than the probability of nonconformance level originally established. This is the desired situation.

Corrective Measures: For some products the variability is excessive and the estimate of the standard deviation large. When this situation exists, the UDL and the LDL may cross one another and an Acceptance Zone does not exist. This means that the desired probability of nonconformance level cannot be achieved without modification of the production process. The process should be evaluated for causes of high product variability, and these causes should be corrected, if possible, to reduce the magnitude of the estimate of standard deviation.

If the average gradation value for the control sieve does not lie within the Acceptance Zone, two courses of action can be taken. One action is to simply increase the accepted probability of nonconformance level. This means an increased risk is accepted of producing a product that will not conform to the specification limits. Increasing the risk is not a desirable course of action. However, because of production constraints and desired product mix at the plant, increasing the risk may be the only feasible action that can be taken. The alternate course of action is to change the plant setup in some appropriate manner to cause the average percent passing value to shift into the Acceptance Zone. Possible changes include crusher setting, screen cloth size or blend proportions.

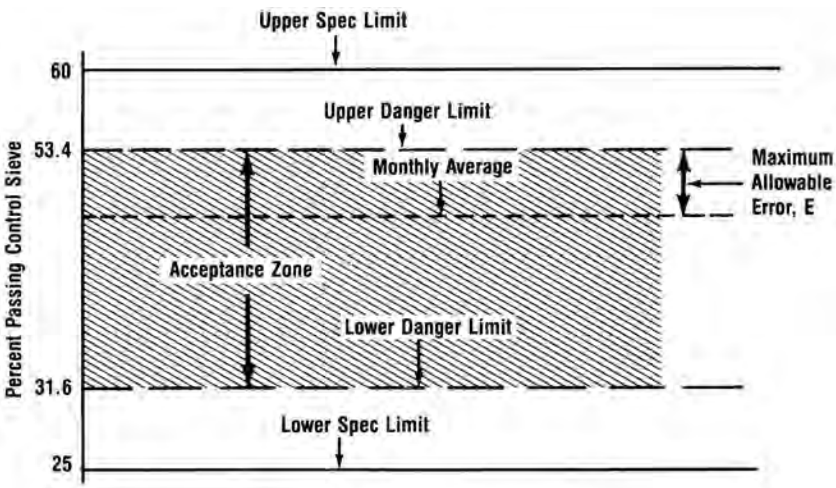

Figure 18.16 Performance chart for control sieve of a given product.

Step 8. Calculate the Maximum Allowable Error (E) associated with the product on the control sieve. The E is calculated by subtracting the average gradation value ($\bar{X}$) for the control sieve from the UDL or by subtracting the LDL from the average gradation value ($\bar{X}$) for the control sieve. The smallest positive value resulting from the calculation is the E for the control sieve for the specific product at the given plant:

$$E = UDL - \bar{X} \tag{18-13}$$

or

$$E = \bar{X} - LDL \tag{18-14}$$

Where all terms have been previously defined.

When the E is equal to or greater than zero, and is less than the numerical difference between the UDL and LDL, the average percent passing value lies within the Acceptance Zone. When the E is greater than the numerical difference between UDL and LDL, the average percent passing value lies outside of the Acceptance Zone. This situation should be corrected if possible. For purposes of subsequent Calculations, the E should be assigned a value of "zero."

When the procedure set forth in Step 8 results in a value that exceeds 4.0 percent, the E should be set at a maximum of 4 percent. Use of 4 percent provides for a reasonable minimum number of test samples for those products that have an average percent passing value that is centrally located relative to the specification limits, but has excessive variability with an estimate of standard deviation greater than 6 percent.

18.25 Probability of Nonconformance with Specification Requirements

The variability of some products is excessive and the estimate of the standard deviation is large. Because of this the Acceptance Zone, if any exists, is small and the average percent passing value may not lie within the Acceptance Zone. In this instance, determine the actual probability of nonconformance (APN) with the specification requirement, rather than increase the probability of nonconformance level repeatedly until a level is reached that is equal to or greater than the actual value. A procedure for determining the APN level is presented below.

Step 1. Establish the position of the average percent passing value ($\bar{X}$) relative to the specification limits for the control sieve. If the average ($\bar{X}$) is within the specification limits, follow Steps 2 and 3; omit Steps 4 and 5. If the average ($\bar{X}$) is outside of the specification limits, follow Steps 4 and 5 and omit Steps 2 and 3.

Step 2. Calculate the difference between the average percent passing value ($\bar{X}$) for the control sieve and both the upper specification limit (USL) and the lower specification limit (LSL):

$$\text{Difference Upper} = \text{USL} - \bar{X} \qquad (18\text{-}15)$$

$$\text{Difference Lower} = \bar{X} - \text{LSL} \qquad (18\text{-}16)$$

Step 3. Using the estimate of the standard deviation (s) established for the percent passing data for the control sieve, calculate the variables A and B as illustrated in Figure 18.17.

Using Table 18.13, calculate the appropriate probability of nonconformance for both A and B as illustrated in the following example. The sum of the two values obtained from Table 18.13 is equal to the APN for the product.

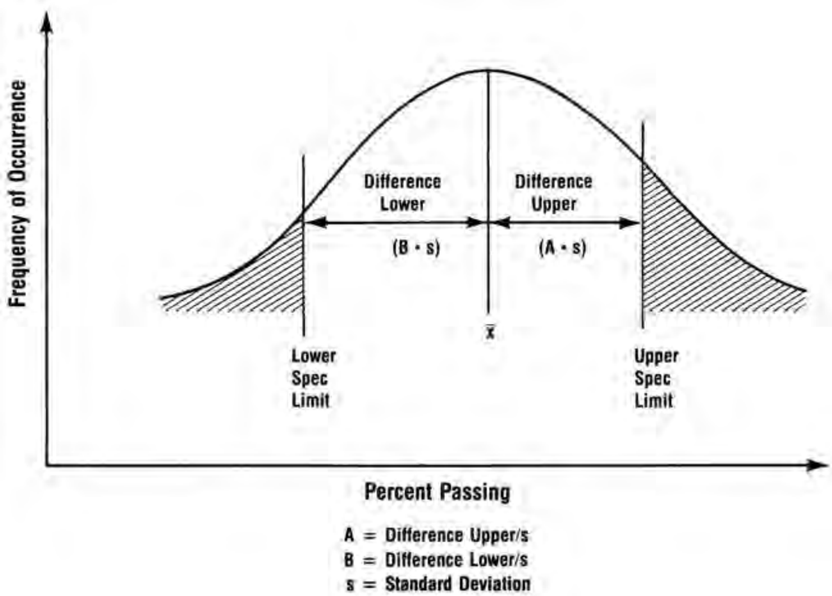

Figure 18.17 Illustrative Example: Within Specification Limits

Assume the average percent passing the control sieve is equal to 52 percent and the estimate of the standard deviation is equal to 7 percent. The specification limits for the control sieve are 25 to 60 percent. Therefore:

Difference Upper = 60.0 - 52.0 = 8.0%

Difference Lower = 52.0 - 25.0 = 27.0%

A = 8.0/7.0 = 1.14; B = 27.0/7.0 = 3.86.

Entering Table 18.13 with the factor A equal to 1.14 gives a probability of nonconformance of 12.71 percent. For a value of B equal to 3.86, Table 18.13 gives a probability of nonconformance of less than 1 percent. The APN for this product on the control sieve is then APN = 12.71 + 1.0 = 13.71 percent.

Step 4. Calculate the difference between the average percent passing value ($\bar{X}$) for the control sieve and the closest specification limit as illustrated in Figure 18.8. Using the estimate of the standard deviation(s) established for the percent passing data on the control sieve, calculate the factor C as shown in Figure 18.18.

Table 18.13 Probability of Noncomformance with Specification for Various Values of Factor when the Average is within the Specification Limits.

Factor	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	49.60	49.20	48.80	48.40	48.01	47.61	47.21	46.81	46.41
0.1	46.02	45.62	45.22	44.83	44.43	44.04	43.64	43.25	42.86	42.47
0.2	42.07	41.68	41.29	40.90	40.52	40.13	39.74	39.36	38.97	38.59
0.3	38.21	37.83	37.45	37.07	36.69	36.32	35.94	35.57	35.20	34.83
0.4	34.46	34.09	33.72	33.36	33.00	32.64	32.28	31.92	31.56	31.21
0.5	30.85	30.50	30.15	29.81	29.46	29.12	28.77	28.43	28.10	27.76
0.6	27.43	27.09	26.76	26.43	26.11	25.78	25.46	25.14	24.83	24.51
0.7	24.20	23.89	23.58	23.27	22.96	22.66	22.36	22.06	21.77	21.48
0.8	21.19	20.90	20.61	20.33	20.05	19.77	19.49	19.22	18.94	18.67
0.9	18.41	18.14	17.88	17.62	17.36	17.11	16.85	16.60	16.35	16.11
1.0	15.87	15.62	15.39	15.15	14.92	14.69	14.46	14.23	14.01	13.79
1.1	13.57	13.35	13.14	12.92	12.71	12.51	12.30	12.10	11.90	11.70
1.2	11.51	11.31	11.12	10.93	10.75	10.56	10.36	10.20	10.03	9.85
1.3	9.68	9.51	9.34	9.18	9.01	8.85	8.69	8.53	8.38	8.23
1.4	8.08	7.93	7.78	7.64	7.49	7.35	7.21	7.08	6.94	6.81
1.5	6.68	6.55	6.43	6.30	6.18	6.06	5.94	5.82	5.71	5.59
1.6	5.48	5.37	5.26	5.16	5.05	4.95	4.85	4.75	4.65	4.55
1.7	4.46	4.36	4.27	4.18	4.09	4.01	3.92	3.84	3.75	3.67
1.8	3.59	3.51	3.44	3.36	3.29	3.22	3.14	3.07	3.01	2.94
1.9	2.87	2.81	2.74	2.68	2.62	2.56	2.50	2.44	2.39	2.33
2.0	2.28	2.22	2.17	2.12	2.07	2.02	1.97	1.92	1.88	1.83
2.1	1.79	1.74	1.70	1.66	1.62	1.58	1.54	1.50	1.46	1.43
2.2	1.39	1.36	1.32	1.29	1.25	1.22	1.19	1.16	1.13	1.10
2.3	1.07	1.04	1.02	0.99	0.96	0.94	0.91	0.89	0.87	0.84

If the factor is greater than 2.30, the probability of nonconformance is less than 1.0%.

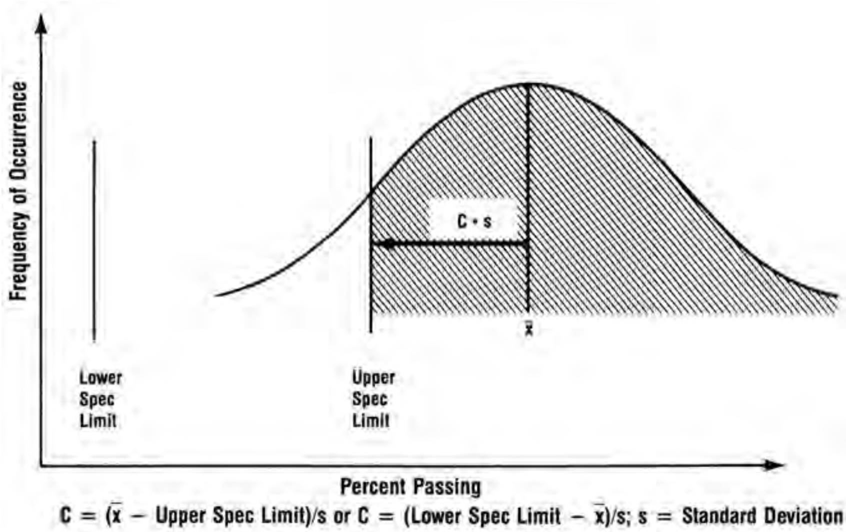

Figure 18.18 Normal distribution curve with average outside of the specification limits.

Step 5. Using Table 18.14, determine the probability of nonconformance for factor C. This value is the APN for the product.

Illustrative Example: $\bar{X}$ Outside of Specification Limits

Assume the average percent passing the control sieve ($\bar{X}$) is equal to 65 percent and the estimate of the standard deviation is equal to 7 percent. The specification limits for the control sieve are 25 to 60 percent. Therefore: C = (65.0 -60.0)/7.0 = 0.71. Entering Table 18.14 with the factor C equal to 0.71 gives an APN of 76.11 percent.

Table 18.14 Probability of Noncomformance with Specification for Various Values of Factor when the Average is Outside the Specification Limits.

Factor	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	50.40	50.80	51.20	51.60	51.99	52.39	52.79	53.19	53.59
0.1	53.98	54.38	54.78	55.17	55.57	55.96	56.36	56.75	57.14	57.53
0.2	57.93	58.32	58.71	59.10	59.48	59.87	60.26	60.64	61.03	61.41
0.3	61.79	62.17	62.55	62.93	63.31	63.68	64.06	64.43	64.80	65.17
0.4	65.54	65.91	66.28	66.64	67.00	67.36	67.72	68.08	68.44	68.79
0.5	69.15	69.50	69.85	70.19	70.54	70.88	71.23	71.57	71.90	72.24
0.6	72.57	72.91	73.24	73.57	73.89	74.22	74.54	74.86	75.17	75.49
0.7	75.80	76.11	76.42	76.73	77.04	77.34	77.64	77.94	78.23	78.52
0.8	78.81	79.10	79.39	79.67	79.95	80.23	80.51	80.78	81.06	81.33
0.9	81.59	81.86	82.12	82.38	82.64	82.89	83.15	83.40	83.65	83.89
1.0	84.13	84.38	84.61	84.85	85.08	85.31	85.54	85.77	85.99	86.21
1.1	86.43	86.65	86.86	87.08	87.29	87.49	87.70	87.90	88.10	88.30
1.2	88.49	88.69	88.88	89.07	89.25	89.44	89.62	89.80	89.97	90.15
1.3	90.32	90.49	90.66	90.82	90.99	91.15	91.31	91.47	91.62	91.77
1.4	91.92	92.07	92.22	92.36	92.51	92.65	92.79	92.92	93.06	93.19
1.5	93.32	93.45	93.57	93.70	93.82	93.94	94.06	94.18	94.29	94.41
1.6	94.52	94.63	94.74	94.84	94.95	95.05	95.15	95.25	95.35	95.45
1.7	95.54	95.64	95.73	95.82	95.91	95.99	96.08	96.16	96.25	96.33
1.8	96.41	96.49	96.56	96.64	96.71	96.78	96.86	96.93	96.99	97.06
1.9	97.13	97.19	97.26	97.32	97.38	97.44	97.50	97.56	97.61	97.67
2.0	97.72	97.78	97.83	97.88	97.93	97.98	98.03	98.08	98.12	98.17

18.26 Establishing Testing Frequency for an Accepted Level of Nonconformance with Specification Requirements

This section presents a simple procedure for calculating how many individual test results must be included in a sample. Using this number of tests allows estimating, with a prescribed precision, the average value of the percent passing the control sieve that would be established if all possible tests were performed for a given quantity of the product or within a given time period. The procedure is developed from information presented in ASTM E122, Standard Recommended Practice for Choice of Sample Size to Estimate the Average Quality of a Lot or Process.[11]

Use of the procedure in evaluating present product quality and testing practice permits reduction in the number of tests presently being performed on some products, more efficient use of Quality Control personnel and more effective inspection of all products being produced. The end-result is improvement of the quality of many of the products being produced, greater conformance with specification requirements, and a reduction in the potential for product liability claims for nonconformance with specifications. Historical information about the product as produced using a given plant setup is utilized in the procedure. This information consists of the average percent passing value and the estimate of the standard deviation associated with the data for the control sieve. The E is established by the procedure given in Step 8 of Section 18.24.

18.27 Procedure for Establishing Testing Frequency

The equation for calculating the minimum number of tests (n) to be included in a sample is as follows:

$$n = \left(\frac{1.96s}{E}\right)^2 \qquad (18\text{-}17)$$

where

- s = advance estimate of the standard deviation of the lot or process for the control sieve
- E = the Maximum Allowable Error between the estimate of average percent passing made from the sample and the true average value that would result by measuring all elements in the lot or process
- 1.96 = a factor corresponding to a 5% probability (5 in 100) that the difference between the sample average and the true average percent passing value in the lot or process is greater than the Maximum Allowable Error (E)

Equation 18-17 gives the number of tests (n) that must be performed in order that the true average percent passing lies within a range defined by the sample average calculated from these tests plus or minus the E with a 95 percent level of confidence.

Example Calculation

Assume that the following data have been established for a product being produced at a given plant:

1. Average percent passing the control sieve for previous month equals 32.6 percent.
2. Estimate of standard deviation for the control sieve established for data set from the previous month equals 4 percent.
3. Specification limits for the control sieve equals 25-60 percent passing.
4. E equals 1 percent.

Using Equation 18-9, the maximum number of tests is $n = (1.96 \times 4.0/1.0)^2 = 62$. At least 62 tests must be performed on this product during the current month to permit determination of an average percent passing value ($\bar{X}_{62}$) that is an estimate of the true average percent passing value for the control sieve of the given product. Considering the sample average determined for the previous month, then the range within which the true average lies is $\bar{X} \pm E$, or 32.6% ± 1.0 percent, giving a variation from 31.6 to 33.6 percent.

The LDL for this example is 31.6 percent. Consequently, as long as the true average is expected to lie above this value with a high degree of confidence, then the assumption is made that the true average lies in the Acceptance Zone. Therefore, the process results in the product having the accepted probability of nonconformance with the specifications.

For these conclusions to be valid, the product must be produced by the same methods that were utilized during the previous month. If the plant setup is changed, the estimate of the standard deviation used in the calculation may or may not be valid. If the standard deviation varies, the required number of tests calculated using equation 16-9 is in error.

Practical Considerations for Number of Tests

Some practical considerations involving the required number of tests obtained using Equation 18-9 are as follows:

1. At least five tests should be performed during a given month on any product that is being produced, irrespective of the value of n established from Equation 18-9.
2. The E used in the equation should be limited to a maximum of 4 percent. If the procedure given in Section 18.4 results in a E greater than 4 percent, assign it a value of 4 percent. Use E equal to 4 percent in all subsequent calculations. This procedure results in the calculation of a reasonable minimum number of samples for situations where the average percent passing is centrally located relative to specification limits, but product variability is excessive.
3. If the calculated minimum number of tests (n) exceeds 150, consider using one of the following alternatives: (a) Sample and test each haul unit (truck or railroad car) and accept or reject each shipment based on the results obtained. (b) Evaluate and reduce product variability. (c) Change the average gradation of the product being produced by the changing the crusher setting, screen cloth size, blend proportions, etc. Any changes made should be selected to shift the percent passing value for the control sieve toward the midpoint of the specification requirements. Repositioning the average value increases the value of the E that can be permitted. An increase in E in turn reduces the required minimum number of tests, while at the same time maintains the accepted probability of nonconformance level.

Graphical Solution for Number of Tests

The graphical solution of Equation 18-9 for calculating the minimum number of tests required is given in Figure 18.19.

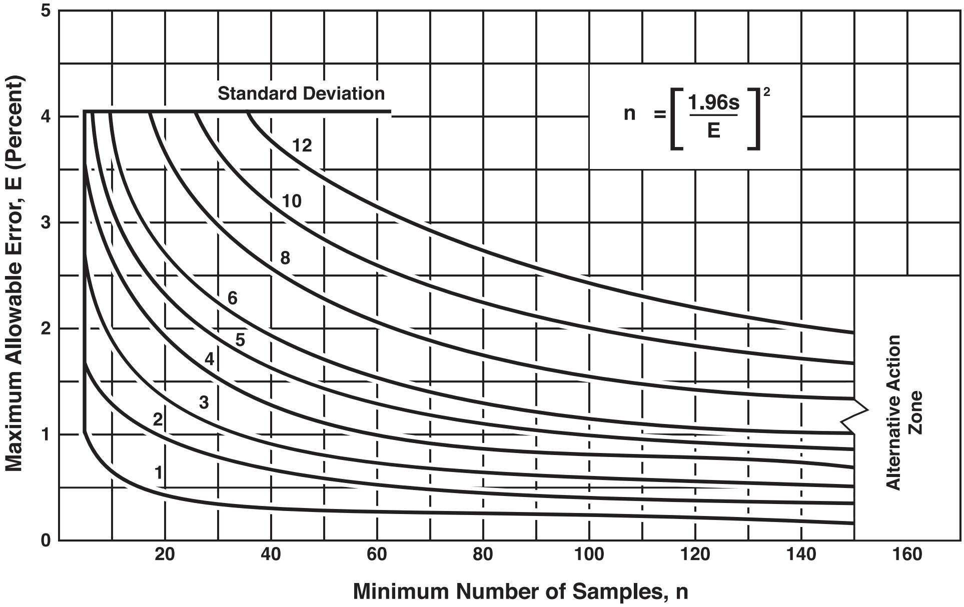

Figure 18.19 Graphical Solution for Minimum Number of Tests

18.28 Control Charts for Determining When Process is Out of Control

Control charts are used to monitor a process during production, and to discover whether or not observed values differ from an expected value by an amount greater than should be attributed to chance.[12] Control charts are used to minimize production of large quantities of non-specification material with associated cost and product liability. Control charts provide information on three aspects which need to be known as a basis for action:

1. Basic variability of the quality characteristic;
2. Consistency of performance; and
3. Average level of the quality characteristic.

Consider the situation when a control chart indicates all of the product cannot be produced within specification limits and when the specifications cannot be changed. The alternatives are either to make a fundamental change in the production process that reduces the basic variability, or to accept the fact that separating good product from bad product is necessary. Sometimes the control chart indicates so much variability that some product is certain to be outside the tolerance. A review of the operation may show that the tolerances are tighter than necessary for proper functioning of the product. The appropriate action may be to initiate efforts to widen the tolerances of the specification.

The control chart indicates when, and in some instances suggests where, to look for the problem. The control chart also indicates when to leave a process alone. The elimination of assignable causes of erratic fluctuation is described as bringing a process under control and is responsible for many cost savings resulting from the application and use of statistical quality control procedures.

The basic variability of a process may be under control and show a consistent pattern of variability. The product, however, may be unsatisfactory because the average level of the quality characteristic is too low or too high. This condition is also disclosed by a control chart. Correcting the average level of the product characteristic may be a simple matter such as changing a crusher setting or screen cloth size. In other situations correcting the characteristic can require a program of research and development.

Once a process is under control at a satisfactory level and with satisfactory limits of variability, the product being produced will meet specifications with an accepted probability of nonconformance level. Under these favorable circumstances it may be possible to reduce the number of test samples required, thus achieving substantial cost savings. An alternative is to redirect the testing effort and concentrate on products that have the greatest potential for problems.

18.29 Benefits Derived from Use of a Control Chart

A control chart, when properly constructed and used by either the quality control technician or the plant superintendent, provides the following benefits:

1. An easily interpreted and current picture of how the process is behaving.
2. Reduces unnecessary adjustments to the process and eliminates searching for nonexistent assignable causes.
3. Pinpoints where the process is actually changing so that action can be instituted to establish and correct assignable cause(s).
4. Improves the quality of the product solely by the attention that is focused on the behavior of the process.

18.30 Constructing a Control Chart

Whenever the data are collected periodically one should always start off utilizing charts for individual values and ranges, XmR charts. This will ensure any of the information concerning changes in the process is not missed. Especially when beginning evaluation of a process with little data, it is best to begin measuring fewer parameters more frequently and use individual values. If later it is determined that changes are slow relative to the sample frequency, you can investigate utilizing subgrouped data.

Sometimes the statistical nomenclature gets in the way of communication between technical, operational and maintenance personnel. Consider using the following:

- Instead of Statistical Process Control, use Continual Improvement or Optimization.
  - This draws attention to improvement rather than monitoring and maintaining.
- Instead of control charts, use process behavior charts.
- Instead of in-control or out-of-control, use predictable or unpredictable process.
- Instead of in-control or out-of-control point, use point outside or inside the limits.
- Instead of control limits, use natural process limits.

Begin by deciding what should be measured. Typically aggregates producers measure gradation, L.A. Abrasion and specific gravity on a regular basis. These are all good measurements to evaluate. Gradation is dependant upon the configuration of the crushers, screening efficiencies and any handling during production and loadout operations. When evaluating gradation, one should select the sieves for sizes which either have a specification or are affected by the process.

Calculating Values For Control Chart

Collect the data and calculate the values needed to construct a behavior chart for the production process.

1. Use individual values to calculate the *average*, $\bar{X}$

2. Calculate the moving ranges. The difference between each individual value.

3. Calculate the *average moving range*, $\overline{mR}$. This is the central or average for the *mR* chart

4. Determine the *upper natural process limit* (UNPL) for the X chart by multiplying the average moving range (from step 3) by 2.66 then add this to the average.

$$UNPL = \bar{X} + (2.66 \times \overline{mR}) \quad (18\text{-}18)$$

5. Determine the *lower natural process limit* (LNPL) for the X chart by multiplying the average moving range (from step 3) by 2.66 then subtract this from the average.

$$LNPL = \bar{X} - (2.66 \times \overline{mR}) \quad (18\text{-}19)$$

6. Determine the *Upper Range Limit* (URL) for the mR chart by multiplying the average moving range (from step 3) by 3.27.

$$URL = (3.27 \times \overline{mR}) \quad (18\text{-}20)$$

The constants 2.66 and 3.27 in the equations are factors needed convert the average moving range to obtain the appropriate limits on the chart. Example data obtained for the percent passing the ½ inch sieve for an ASTM No.57 concrete aggregates are given in Table 18.15.

Table 18.15 Example using the ½ inch sieve from an ASTM No. 57 product

Sample ID	Product ID	Date	Type	½" (12.5mm) (cumulative % passing)	Moving Range
-1301108062	1036898	07/29/2011 11:27	Shipping	34.2	
-1301107538	1036898	08/01/2011 08:07	Shipping	46.3	12.1
-1301107270	1036898	08/01/2011 12:06	Shipping	47.2	0.9
-1056661453	1036898	08/02/2011 07:27	Shipping	49.0	1.8
-1056661187	1036898	08/02/2011 12:07	Shipping	48.2	0.8
-1056660844	1036898	08/03/2011 07:00	Shipping	48.1	0.1
-1056660617	1036898	08/03/2011 12:26	Shipping	44.6	3.5
-1056660119	1036898	08/04/2011 05:28	Shipping	47.0	2.4
-1056659782	1036898	08/04/2011 12:00	Shipping	46.5	0.5
-1811449285	1036898	08/05/2011 06:00	Shipping	43.4	3.1
-1811448736	1036898	08/05/2011 12:41	Shipping	41.8	1.6
-1811448784	1036898	08/08/2011 06:02	Shipping	38.1	3.7
-1811448456	1036898	08/08/2011 12:47	Shipping	38.8	0.7
-1811448174	1036898	08/09/2011 06:01	Shipping	34.8	4.0
-1811447915	1036898	08/09/2011 12:12	Shipping	37.4	2.6
-1811447520	1036898	08/10/2011 06:05	Shipping	48.8	11.4
51697442	1036898	08/10/2011 12:10	Shipping	49.9	1.1
51697820	1036898	08/11/2011 06:00	Shipping	42.2	7.7
51698050	1036898	08/11/2011 12:06	Shipping	42.7	0.5
51698405	1036898	08/12/2011 06:01	Shipping	33.1	9.6
51698644	1036898	08/12/2011 12:03	Shipping	42.7	9.6
51698913	1036898	08/15/2011 06:01	Shipping	38.7	4.0
51699185	1036898	08/15/2011 12:05	Shipping	39.1	0.4
1825547028	1036898	08/16/2011 06:21	Shipping	44.7	5.6
1828397409	1036898	08/16/2011 12:07	Shipping	44.0	0.7
1828397825	1036898	08/17/2011 06:18	Shipping	37.4	6.6
1828398015	1036898	08/17/2011 12:18	Shipping	39.5	2.1
1828398382	1036898	08/18/2011 06:02	Shipping	31.6	7.9
1828398667	1036898	08/18/2011 12:06	Shipping	33.2	1.6
-1935178782	1036898	08/19/2011 06:06	Shipping	31.9	1.3
			Number of Samples	30.0	
			Average	**41.5**	
			Average Moving Range		**3.7**
			Upper Natural Process Limit		**51.4**
			Lower Natural Process Limit		**31.6**
			Upper Range Limit		**12.2**

Creating The Control Chart

Now that the data needed to construct the chart have been obtained, plot the individual values and draw the Average and Upper and Lower Natural Process Limits as shown in Figure 18.20.

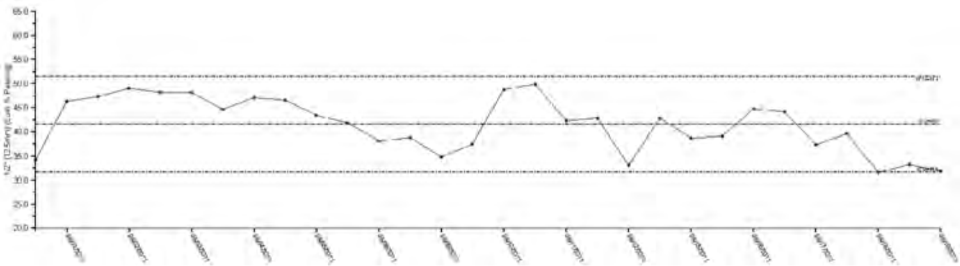

Figure 18.20 Plot of Individual Values and Upper and Lower Process Limits

Plot the Moving Averages and draw the Range Limits as shown in Figure 18.21.

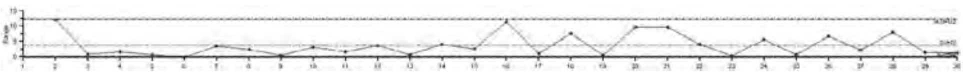

Figure 18.21 Plot of Moving Averages

Interpreting the XmR Chart

The sample to sample variation is seen on the bottom moving range chart. The upper *range limit* of 12.2 means that if the cumulative percent passing the ½ inch sieve on the ASTM No. 57 product changes by more than 12.2 from one sample to the next and the reason should be determined. A change of this amount is excessive and likely to be from some assignable cause.

The individual sample values are seen on the upper Individual values chart. The limits on this chart tell us how large (high) or small (low) a single sample result must be before it is a definite departure from the historic average. In our example a sample result in excess of 51.4 cumulative percent passing would be a signal that the percent passing the ½ inch sieve has shifted up. A value below 31.6 would indicate a signal of the percent passing shifting downward.

In this example, all of the individual values are within the natural process limits (although some are close). Therefore, this process is predictable or in control. These natural process limits are the *voice of the process*. Some may be concerned about natural process limits going from 31.6 to 51.4. However, they indicate what the process can deliver, unless there are fundamental changes to the process.

If the amount of variation in the Natural Process Limits is considered to be excessive, adjustments should be made to the process.

Determining Whether or Not Material is Acceptable to Customer

The next step is to apply the project specifications to the Process Behavior chart to determine if material being produced is acceptable to the customer. In Figure 18.22, the ASTM #57 specification for the ½ inch sieve; 25 to 60 percent passing is applied.

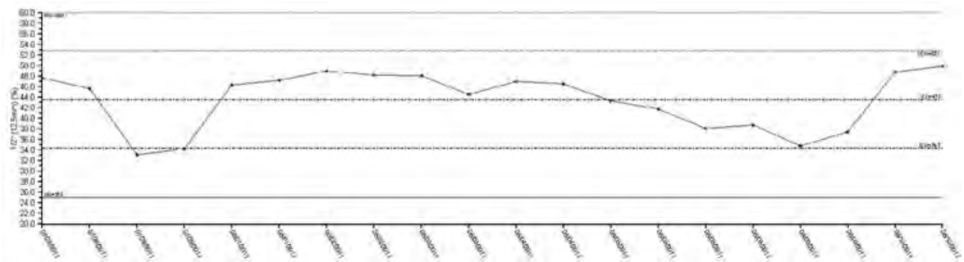

Figure 18.22 Process Behavior Chart with ASTM No. 57 specification applied.

The Process Behavior Limits fit well within the specifications, so one can be confident that the material being produced is in compliance with specifications, and should continue to be in specifications unless something changes. If the process is predictable, but does not meet specification requirements, either the process will have to be modified or the specification changed.
So what to do now? Continue measuring and adding each point to the Process Behavior Chart. Each time a data point is added, determine if it is within Upper and Lower Natural Process Limits. If not within Natural Process limits, it is considered a signal that something has changed and the assignable cause should be investigated so it can be removed from the process.

Generally there is no reason to revise Natural Process Limits unless you have a change in the process. Once a change has been made, new Natural Process Limits must be calculated,.
Sometimes when the cause of a signal has been removed, the limits may need to be revised.
Guidelines for changing limits:

- Do the data exhibit different behavior?
- Is the reason for the change known?
- Is the change desirable?
- Is the change expected, and will it continue?

If the answer is yes to all four bullets, then revise the targets.
If the answer to 1 is no, then do not change targets.
If the answer to 2 is no, do not change limits and work to remove the assignable causes.
If the answer to 3 is no, do not change limits and work to remove the assignable causes.
If the answer to 4 is no, do not change limits and work to remove the assignable causes.

What Is Considered To Be A Signal

It is important to interpret signals and trends in the context of the test data. Points outside the control limits are obvious signals, and any consistent pattern that makes sense given the context of the data may be a signal.

There are guidelines for signal detection. The most widely used are The Western Electric Zone Rules.[17]

- **Detection Rule One**
  Look for a dominant assignable cause whenever a single point falls outside the natural process limits (3 sigma) on either the individuals or the moving range chart indicates a large process change. The further the data point is outside of the limit, the stronger the signal and more likely a change has occurred. False signals are rare, and the data point will be closer to the limit. The more data points outside of the limits and the further away from the limits, the higher the confidence that the process is not in control. See Figure 18.23 below.

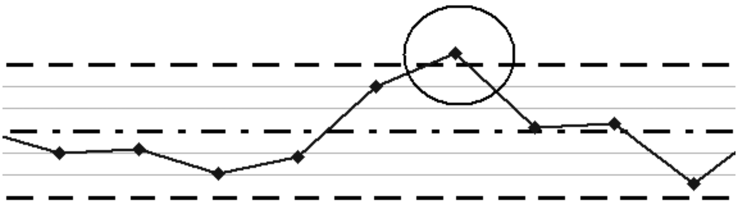

Figure 18.23 Single Point on X-chart Outside of the Control Limits

- **Detection Rule Two**
  Two out of three successive values on the same side of the average on the x-chart and both greater than two-sigma away from the average indicates a moderate shift in the process. See Figure 18.24 below.

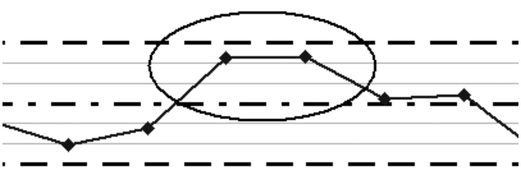

Figure 18.24 Two Out of Three Successive Values on the X-chart on the Same Side of the Average and Greater Than Two-sigma from Average

- **Detection Rule Three**
  Four out of five successive values on the x-chart on the same side of the average and more than one-sigma away from the average indicates a small to moderate shift in the process. See Figure 18.25 below.

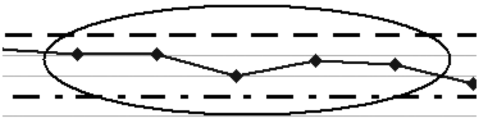

Figure 18.25 Four Out of Five Successive Values on the X-chart on the Same Side of the Average and More Than One-sigma from Average

- **Detection Rule Four**
  Eight successive values on the same side of the average indicate a small but sustained shift in the process. See Figure 18.26 below.

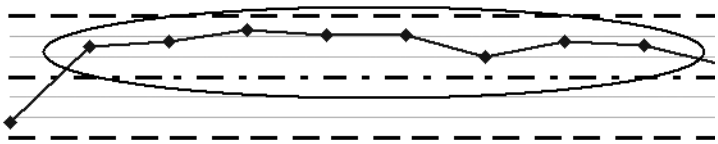

Figure 18.26 Eight Consecutive Values on X-chart on the Same Side of the Average

Keep in mind that people familiar with the process are the best interpreters of trends occurring in the process. Therefore, the process behavior chart should be made available to all personnel involved in the production process. This will engage as many people who are knowledgeable of the process in the interpretation of the test data, thereby improving process control and product quality.

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Index

A

B

C

D

E

F

G

H

I

J

K

L

M

N

O

P

Q

R

S

T

U

V

W

X, Y, Z

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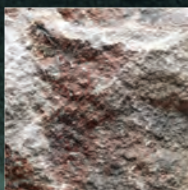

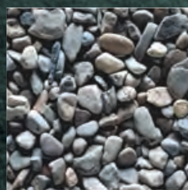

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