



Concrete Craftsman Series

Shotcrete For The Craftsman



CCS-4(20)



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Concrete Craftsman Series

Shotcrete For The Craftsman

Reviewed on behalf of ACI's Educational Activities Committee by:
ACI Committee E703

John L. Hausfeld, Chair

Scott M. Anderson
Paul J. Beagley
Aron J. Csont
Daniel P. Dorfmueller

James J. Ernzen
Leonard J. Gagliardi
Beverly A. Garnant
Michael G. Hernandez

William D. Palmer
Frank Townsend
Thomas G. Tyler
Kimberley E. Wilson

This education document for the shotcrete craftsman was prepared by ACI Committee E703, Concrete Construction Practices, with substantial input from ACI Committee C660, Shotcrete Nozzleman Certification, and is based on the previous booklet prepared by Jean-François Dufour, Marc Jolin, Lars Balck, Steven Gebler, Merlyn Isaak, Dudley Morgan, and Philip Seabrook. Review of this education document was performed by the above-mentioned original authors and additional ACI C660 members including Charles Hanskat, Raymond Schallom, Oscar Duckworth, and Randle Emmrich, who were all key in the improvement and support of this new document.

The authors would like to both recognize and thank all ACI C660 members for their dedication to the improvement of shotcrete practices throughout the industry, with thanks to Merlyn Isaak who was C660 Chair during development and launch of the ACI Shotcrete Nozzleman Certification Program in 2001. Special recognition goes to Theodore Crom who was the inspiration for Shotcrete Nozzlemen Certification.

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Concrete Craftsman Series:
CCS-4 Shotcrete For The Craftsman
ISBN 978-1-64195-113-5
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Managing Editor: Katie A. Amelio, P.E.
Engineering Editors: Katie A. Amelio, P.E.
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Art Program: Robert Hogston and Aimee Kahaian
Production Editors: Kelli Slayden, Kaitlyn Dobberteen,
Tiesha Elam, Hannah E. Genig
Page Design & Composition: Ryan Jay
Manufacturing: Marie Fuller

First Printing: October 2020
Printed in Eau Claire, Wisconsin.

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
USA
www.concrete.org
+1.248.848.3700

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PREFACE

The purpose of this document is to provide the nozzleman an understanding of basic concrete technology and describe and illustrate how to properly place quality shotcrete.

Information in this workbook should be used as a guide to good practice. ACI 506.2, “Specification for Shotcrete,” and ACI 506R, “Guide to Shotcrete,” should also be consulted. Above all, the plans and specifications for a specific construction project must be followed.

CHAPTER 1—WHAT IS SHOTCRETE?

Shotcrete is concrete conveyed through a hose and pneumatically projected at high velocity onto a surface to achieve compaction. It is a method of placing concrete used primarily in vertical and overhead surfaces. Shotcrete allows construction of walls and other structures with no form or only a one-sided form. It is often more economical than form-and-pour concrete because of its versatility and substantially reduced formwork. Tanks, swimming pools, tunnels, mines, sculptured rocks, structural walls, high-rise basements, erosion control embankments, retaining walls, and shear walls are all examples of new concrete structures commonly built using shotcrete. In addition, a wide variety of concrete repairs also employ shotcrete.

Shotcrete can be placed at various thicknesses against one-sided forms (or existing concrete or masonry structures and rock, earth, or other surfaces). Thickness of the material placed varies depending on several parameters, further described in Chapter 8, Shotcrete Placement Principles and Techniques.

The nozzleman is the craftsman that physically directs the shotcrete placement of the concrete. The nozzleman has final responsibility for the quality of the placed shotcrete and is an extremely important member of the shotcrete crew. The nozzleman should have an understanding of the materials, equipment, safety procedures, and the proper placement techniques to produce high-quality, durable concrete.

Although this document is directed to the nozzleman, they are not the only important person involved in a shotcrete project. The owner, engineer, contractor, job superintendent, foreman, and shotcrete crew are all important. Only with the cooperation and dedication of everyone involved will a project be successful.

1.1—Introduction

The two shotcrete processes are dry-mix and wet-mix.

1.1.1. Dry-mix shotcrete

Dry-mix shotcrete is the process where a dry mixture of concrete materials is conveyed pneumatically (with air flow) through a delivery hose to the nozzle where water is added (Fig. 1.1.1).

In dry mix, all the concrete ingredients, except liquids, are thoroughly mixed together and then fed into a mechanical feeder or gun. The dry concrete material is then carried by compressed air flowing through the delivery hose to a

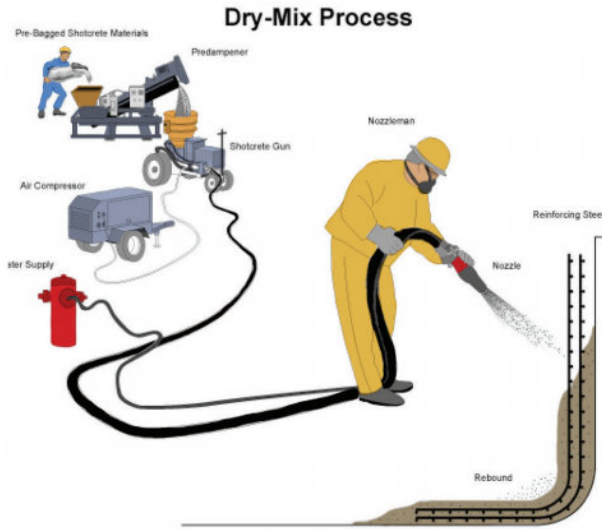


Fig. 1.1.1—Dry-mix shotcrete process.



Fig. 1.1.2—Wet-mix shotcrete.

nozzle body. The nozzle body has an internal water ring where water is injected under high pressure and thoroughly mixed with the concrete ingredients. The concrete is shot from the nozzle at high velocity onto the receiving surface. Mixing of all the concrete materials occurs in the nozzle and as the material impacts the surface.

The term gunite was once proprietary but has become a generic term. The American Concrete Institute adopted the term dry-mix shotcrete as a nonproprietary term for gunite and it is the terminology used in this document.

1.1.2. Wet-mix Shotcrete

The wet-mix process (Fig. 1.1.2) has all the ingredients—including cement, supplemental cementitious materials, chemical admixtures, aggregate, and mixing water—thoroughly mixed before being pumped into a delivery hose or pipeline. Compressed air is injected at the nozzle to increase the material velocity. The concrete is then shot from the nozzle at high velocity onto the receiving surface.

1.1.3 Comparison of the shotcrete processes

Either shotcrete process can produce quality shotcrete suitable for normal construction requirements. Different factors will determine the appropriate process for an application. These factors include experience of shotcrete crew, area of shotcrete to be applied, volume and thickness of shotcrete to be applied, jobsite access, availability of materials, and more.

Table 1.1.3: Comparison of the shotcrete processes

Dry-mix process	Wet-mix process
1. Instantaneous control over mixing water and consistency of the mixture at the nozzle to meet variable field conditions.	1. Mixing water is controlled at the mixing equipment.
2. Capable of being transported longer distances.	2. Less dust rebound during the shooting operation.
3. Delivery hoses are lighter and easier to manipulate.	3. Heavier hoses to withstand higher pumping pressures.
4. Lower volume for a given hose size.	4. Higher volume for a given hose size

Table 1.1.3 gives differences in operational features and other properties between the dry-mix and wet-mix shotcrete processes that may merit consideration.

Shotcrete is inherently high-quality concrete with a low water-cementitious materials ratio (w/cm) and a high percentage of cementitious material content (Chapter 5). Shotcrete acquires some of its unique properties from the placement process as the concrete is compacted when it impacts the surface. Therefore, it is important that shotcrete impact at high velocity to achieve compaction. The nozzleman is responsible for ensuring that shotcrete is properly placed. The quality of shotcrete in place is largely dependent upon the skill, knowledge, and careful attention of the nozzleman.

Shotcrete nozzling is complex and physically demanding. It should not be undertaken by anyone with physical limitations.

Considering that shotcrete is a method of placing concrete, it requires experienced nozzlemen, properly sized and maintained delivery equipment, and shotcrete mixtures appropriate for the type of work undertaken.

CHAPTER 2—WHAT THE SHOTCRETE CRAFTSMAN SHOULD KNOW ABOUT CONCRETE

A shotcrete craftsman should know what concrete is made of and how it behaves when fresh and after it has hardened. Shotcrete craftsmen should also recognize safety precautions needed to protect themselves and their fellow workers when they are placing and finishing concrete.

Understanding the basics of concrete helps craftsmen produce better concrete. Most of this workbook deals with shotcrete, but many of the principles discussed also apply to other types of concrete work.

2.1—What is concrete?

Concrete is the most widely used construction material today. Worldwide approximately 1 ton (900 kg) is produced every year for every living human being. NRMCA data suggest U.S. concrete production is approximately 350 million cubic yards (9.5 billion cubic ft) of concrete each year. This is approximately 2 tons (4000 pounds) per person, but worldwide usage estimates are lower per capita. Low cost and availability of concrete drive the high level of concrete consumption. Fortunately, along with low cost, concrete is also strong and durable, resistant to water and fire, and readily formable to an infinite variety of sizes and shapes (a key advantage for shotcrete).

The success of concrete construction depends on the concrete developing the strength, low permeability, and other properties that the designer specified when the work was planned. Many factors in placing concrete in the field can directly affect the quality and durability of the final in-place concrete. Because shotcrete crews work with concrete, they should understand the important factors affecting the properties of concrete.

Concrete is a mixture of two main components, described in the following.

2.1.1 Aggregates

Aggregates are generally divided into two groups: fine and coarse. Fine aggregates consist of natural or manufactured sand with particle sizes ranging up to 1/4 in. (5 mm). Coarse aggregates are those with most particles sizes above 1/4 in. (5 mm) and ranging up to 6 in. (150 mm). The most commonly used maximum aggregate size in form-and-pour concrete is 3/4 to 1.5 in. (20 to 40 mm). Shotcrete aggregate typically tends to be 3/8 in. (10 mm) or less (3.3).

Because aggregates make up to approximately 70 to 80 percent of the total weight of concrete, their selection is important. Aggregates should have adequate strength and resistance to exposure and not contain materials that can cause deterioration of the concrete. Refer to Table 2.1.1 for example of harmful substances in aggregates. A good gradation of aggregate (a mixture of different sizes) is desirable for reducing the volume of space between the aggregate particles to minimize the volume of cement paste.

2.1.2 Paste

Paste is made of cementitious materials (cement) and/or supplementary cementitious materials (such as silica fume, fly ash, or slag). It is the glue that binds the aggregates (sand and gravel or crushed stone) into a rocklike mass when the paste hardens due to the chemical reaction of the cement and water (Fig. 2.1.2a).

The term cement used throughout this section refers to portland cement unless otherwise stated (3.1). The mixture of cement, water, and aggregates are sometimes referred to as cement, but this is technically wrong; the mixture of ingredients is concrete. Only the binding powder is properly called cement.

The paste is composed of cement and other supplemental cementitious materials (such as silica fume, fly ash, or slag), potable water, and entrapped air or purposely entrained air. Cement paste ordinarily constitutes approximately 20 to 30 percent of the total weight of concrete. Figure 2.1.2b shows that the total weight of cement is usually between 13 and 20 percent and the water between 7 and 10 percent in a typical concrete mixture. Total air content in air-entrained concrete ranges from 3 to 8 percent of the volume of the concrete, depending on the maximum size of the coarse aggregate. A typical concrete mixture proportioned by weight is presented in Fig. 2.1.2b(a). A typical shotcrete mixture proportioned by weight is presented in Fig 2.1.2b(b).

The quality of the concrete is highly dependent on the quality of the paste. In properly made concrete, all the space

Table 2.1.1: Most common harmful substances in aggregates

Item	Fine aggregate	Coarse aggregate
Clay lumps and friable particles	Unsound particles may affect durability and workability, cause pop-outs, and increase water demand of mixture	
Fine particles (less than 0.0031 in. or 80 μm)	Affect bond of paste to aggregate and increase water demand	Can cause trouble when it exists as a coating on coarse aggregate
Soft particles	—	Reduce durability and surface hardness

between aggregate particles are filled with paste, as illustrated in Fig. 2.1.2a. Chapter 3 also provides further information on the various types of portland cement.

With a specific concrete mixture and curing conditions, the quality of the hardened concrete is determined by the amount of water used in comparison to the amount of cement. Some advantages of reducing water content follow:

- a) Increased compressive strength and flexural strength
- b) Lower permeability and absorption
- c) Increased resistance to weathering
- d) Better bond between successive layers and between concrete and reinforcement
- e) Reduced tendency to crack due to shrinkage

In other words, higher-quality, more durable concrete has less water for a given amount of cement provided it can be consolidated properly.

2.2—Fundamentals of concrete

The term concrete used in this section is for the basic characteristics applicable to form-and-pour, cast-in-place, or shotcreted. Because shotcrete is concrete, this basic concrete knowledge is essential information for the shotcrete craftsman. Specific requirements for concrete to

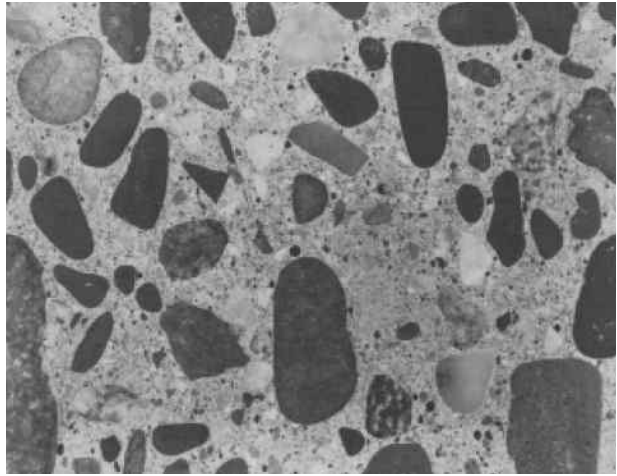


Fig. 2.1.2a—Polished section sawed from concrete. The cement-and-water paste fills all spaces between the aggregate particles (photo courtesy Portland Cement Association).

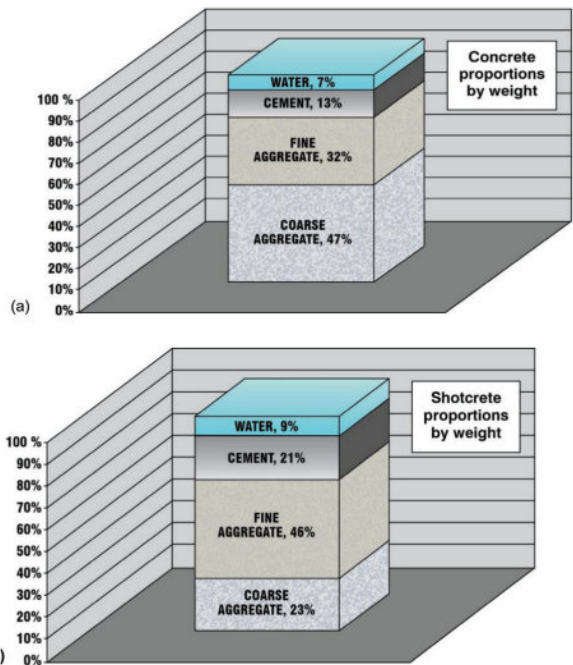


Fig. 2.1.2b—(a) Proportions by weight of materials in a typical concrete mixture; and (b) proportions by weight of materials in a typical shotcrete mixture.

be placed by shotcreting is described in more detail in Chapters 4 to 12.

2.2.1 Freshly mixed concrete

Freshly mixed concrete should be plastic or semi-fluid and generally be capable of being molded by hand. A very fluid concrete mixture can be molded in the sense that it can be cast in a mold.

In a plastic concrete mixture, all the grains of sand and pieces of rock are encased and held in suspension by the paste. The ingredients are not apt to segregate (separation of the aggregate from the paste) during transport; and when the concrete hardens, it becomes a relatively uniform mixture of all the components. Properly designed concrete of plastic consistency does not crumble but flows sluggishly without segregation.

2.2.2 Workability

Workability refers to the ease of placing, consolidating, and finishing freshly mixed concrete. Concrete should be workable and should not segregate or bleed excessively. Bleeding is a normal process of the migration of water to the top surface of freshly placed concrete caused by the settlement of the solid materials. Settlement is caused by the combined effect of vibration and gravity.

Excessive bleeding increases the water content near the top surface of the placed concrete. A weaker top layer of concrete with poor durability may result, particularly if finishing operations take place while bleeding water is present. It is important to transport and place each load as close as possible to its final position. Entrained air and water-reducing admixtures improve workability and reduce the tendency of freshly mixed concrete to segregate and bleed (2.2.10).

Slump is used as an indication of the workability of concrete (Fig. 2.2.2). Slump measurement is a standardized

test method that places a sample of fresh concrete in a cone-shaped mold and consolidates it by rodding. The mold is raised, and the concrete allowed to subside. The vertical distance between the original height (12 in. [300 mm]) and the displaced slumped position of the center of the top surface of the concrete is measured and reported as the slump of

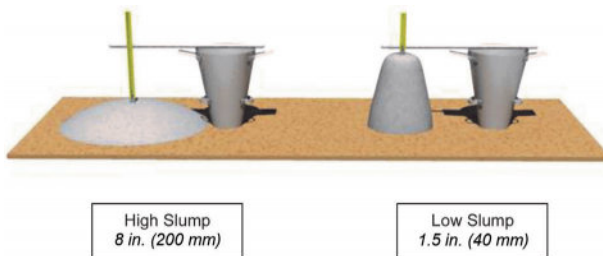


Fig. 2.2.2—Measure of workability of concrete (high slump versus low slump).

the concrete. A low-slump concrete has a stiff consistency. Higher slump means a more flowable mixture. In construction practice, thin concrete members and heavily reinforced concrete members require higher slump. A plastic mixture, which does not segregate, is required for maintaining homogeneity during handling and placement.

While a low-slump concrete with limited amounts of convenience water is suitable for most concrete work, high-range water-reducing admixtures (3.5) may be used to make high-slump concrete that flows better in thin or heavily reinforced formed concrete members.

2.2.3 Consolidation

In poured concrete, proper consolidation is achieved by mechanical vibration. It may also be consolidated by hand rodding, if the concrete mixture is workable enough. With adequate consolidation, stiffer mixtures can be used resulting in improved quality, durability, and economy. In the shotcrete process, as described in Chapter 1, proper consolidation is achieved by compaction of the concrete by impact at high velocity.

2.2.4 Hydration, setting time, hardening

The binding quality of cementitious material results from a chemical reaction between the cementitious material and water, called hydration. The product of this chemical reaction is hydrated cement paste. Strength of concrete depends on the strength of the paste, the strength of the aggregate, and the bond between the paste and the aggregates.

The different chemicals making up cement react differently from one another. Some will react early and quickly, while others will take more time to activate and then will react slowly over time. It is by changing the relative proportions of some of these constituents and by changing the fineness of the powders, that different types of portland cements can be produced (3.1 for additional information).

Hardened cement paste forms dense, bonded aggregations that adhere to grains of sand and to coarse aggregate, cementing everything together. This results in concrete setting, hardening, and gaining strength.

The hardened concrete contains small pores filled with water and air that have no strength. The strength is in the solid part of the paste. The less porous the hardened cement paste, the stronger and the more durable the concrete. When mixing concrete, no more water should be used than is absolutely necessary to make the concrete plastic and workable. Even then, the water used is usually more than is



required for hydration of the cement to achieve the desired strength.

Knowledge of the amount of heat released as cement hydrates can be useful in planning construction. In cold weather, concrete needs to be protected from freezing. In hot weather, concrete needs additional protection from drying out during the initial and final curing period.

Knowledge of the rate of reaction between cement and water is important because the rate determines the time of setting and hardening. The initial reaction should be slow enough to allow time for the concrete to be transported, placed, consolidated, and finished. Care should be taken in warmer weather because higher mixture temperature may speed up the hydration reaction, reduce the setting time, and limit the workability period of the concrete. Factors that influence the rate of hydration include concrete temperature, ambient temperature, the size and thickness of the concrete member, amount of water added, cement type and amount, and admixtures present in the mixture.

2.2.5 Curing

Because it is the chemical reaction between water and cement, called hydration, that generates the paste in the system, it is important to keep water available until the required strength has been reached. Concrete continues to gain strength with age as long as any unhydrated cement is still present, provided the concrete remains moist or has a relative humidity above approximately 90 percent and the concrete temperature remains favorable. When the relative humidity within the concrete drops below approximately 90 percent or the temperature of the concrete drops below freezing, hydration and strength gain stop. Premature interruption of strength gain should be avoided through proper curing and protection of concrete.

However, if concrete is resaturated after a drying period, partial hydration is resumed and some strength gain may occur provided it was not frozen. It is best to cure concrete continuously from the time it is placed until it has attained the desired level of hydration and corresponding strength and permeability. Proper curing also reduces the potential for the development of drying shrinkage cracks.

2.2.6 Drying of concrete

Concrete does not harden by drying. As mentioned previously, concrete should continue to hold enough moisture throughout the curing period for the cement to hydrate. Freshly cast concrete generally has more water than needed

for hydration, but as drying progresses from the surface inward (in the absence of curing or when curing is stopped), strength gain will stop when the relative humidity gets below 90 percent. A common illustration of this is the surface of a concrete floor that has not had sufficient curing. Because it has dried too quickly, concrete at the surface is weak and traffic on it can create dusting. Similarly, if concrete is placed on a very dry absorptive surface, a weakened plane will result due to the water required for hydration being absorbed out of the concrete.

Also, when concrete dries, it shrinks, just as wood, paper, and clay do. Drying shrinkage is one of the primary causes of cracking, and the width and frequency of cracks are a function of the rate of drying. While the exposed surface of concrete will dry quite rapidly, it takes a much longer time for the concrete below the surface to dry. Thus, size, shape, and exposure conditions of a concrete member strongly influence the rate of drying. Concrete elements with large surface area in relation to volume (such as thin repairs) dry faster than large concrete volumes with relatively small surface areas (such as bridge piers or retaining walls). Additional information is presented in 2.2.13, Control of cracking.

2.2.7 Strength

The usual measure of strength of concrete is called compressive strength. It is expressed in psi (pounds per square inch) or in metric units MPa (megapascals) and is designated by the symbol f_c . It is usually measured at a concrete age of 28 days, although some methods allow for measurements as early as 2 hours. In North America, compression tests of concrete are usually made on cylinders cast in molds at the time of delivering or placing concrete. Standard test cylinders have either a 6 in. (150 mm) diameter and 12 in. (300 mm) height or a 4 in. (100 mm) diameter and 8 in. (200 mm) height.

Compressive strength of concrete is a primary physical property and one frequently used in design calculations for concrete structures that must carry loads. Most poured concrete has compressive strength in the range of 3000 to 5000 psi (20 to 35 MPa). Continuing advances in concrete technology are, however, making ever-higher strengths available. Good quality shotcrete has compressive strengths that typically range from 4000 to 8000 psi (28 to 55 MPa). With silica fume and high-quality aggregates, shotcrete strengths can reach up to 12,000 psi (80 MPa).

Strength of concrete is strongly affected by the proportion of water and cement in the mixture (commonly called water-cement ratio $[w/c]$, which will be described further in

Chapter 5), the age of the concrete, and the extent to which hydration has progressed.

2.2.8 Unit weight (density)

Conventional concrete, normally used in pavements, buildings, and other structures, weighs between 137 and 150 lb/ft³ (2200 and 2400 kg/m³). Special heavyweight concretes, used in counterweights or radiation shielding, weigh up to 200 lb/ft³ (3200 kg/m³). The unit weight (density) of concrete varies depending on the amount and relative density of the aggregate; the amount of air that is entrapped or purposely entrained; and the cement paste content, which is influenced by factors such as the maximum-size aggregate and chemical admixtures used. In the design of reinforced concrete structures, the combination of conventional concrete and reinforcing bars is commonly assumed to weigh approximately 150 lb/ft³ (2370 kg/m³).

2.2.9 Resistance to freezing and thawing

Concrete is expected to have long life and low maintenance. It should have good durability to resist the anticipated exposure conditions. One of the most destructive weathering factors is freezing and thawing while the concrete is wet, particularly in the presence of deicing salts. The freezing of the water in the paste, the aggregate particles, or both is the cause of deterioration.

With proper air entrainment, concrete is much more resistant to deterioration from freezing and thawing than non-air-entrained concrete, as shown in Fig. 2.2.9. During freezing, the water expands and the air bubbles in the paste provide chambers for the water to enter and thus relieve the pressure generated. Deterioration occurs when resulting pressure generated exceeds the tensile strength of concrete, causing internal cracking, surface scaling, or both (refer to 3.5.5 for additional information).

Air-entrained concrete and concrete with a low w/c are much more resistant to damage from freezing-and-thawing cycles than non-air-entrained concrete or concrete with a high w/c .

2.2.10 Permeability and impermeability

Concrete used in water-retaining structures or concrete that is exposed to weather or other severe exposure conditions should be as impermeable as possible. Permeability is a measure of the amount of water that penetrates through concrete. Water readily penetrates high permeability concrete whereas water penetration is much lower in low-permeability concrete. Generally, the same properties of concrete that make

concrete less permeable also make it more watertight and resistant to damage.

A low w/c also reduces segregation and bleeding, further contributing to lower permeability. To prevent water from traveling through a concrete section, the concrete should also be free from cracks and rock pockets or honeycombs.

2.2.11 Abrasion resistance

Structures such as pavements, bridge decks, floors, and hydraulic structures are subject to abrasion, thus these applications require concrete to have a high abrasion resistance. Test results indicate that abrasion resistance is closely related to the compressive strength of concrete and the quality of aggregate used.

2.2.12 Shrinkage

Concrete kept continually moist will expand slightly, but when permitted to dry, concrete will shrink. The primary factor influencing the amount of drying shrinkage is the amount of cement paste and the water content of the paste. Drying shrinkage increases directly with increases in paste and water content.

The amount of shrinkage also depends on several other factors, such as amount of aggregate used, properties of the aggregate, cement type, size and shape of the concrete mass, relative humidity and temperature of the environment, method of curing, degree of hydration, and time.

2.2.13 Control of cracking

The two primary causes of cracks in concrete are:

- 1) Stress due to early-age plastic shrinkage, long-term drying shrinkage, or temperature changes in restrained conditions
- 2) Stress due to applied loads

Early-age plastic shrinkage appears in the surface of fresh concrete soon after it is placed while it is still plastic, and occurs when water evaporation at the surface of the concrete is excessive. Though the surface concrete loses water due to evaporation, the inner portions of the concrete section

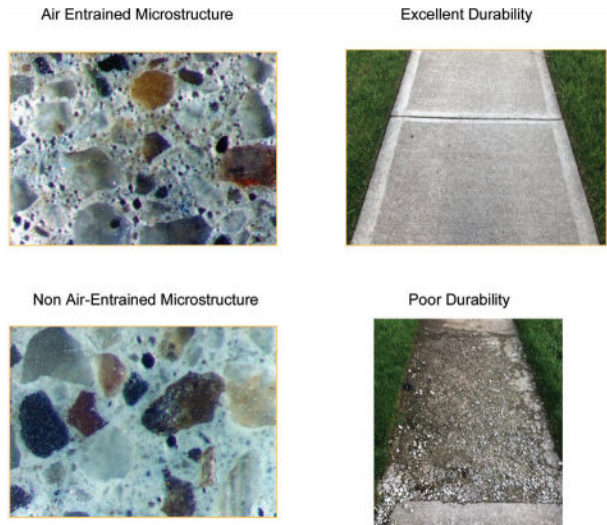
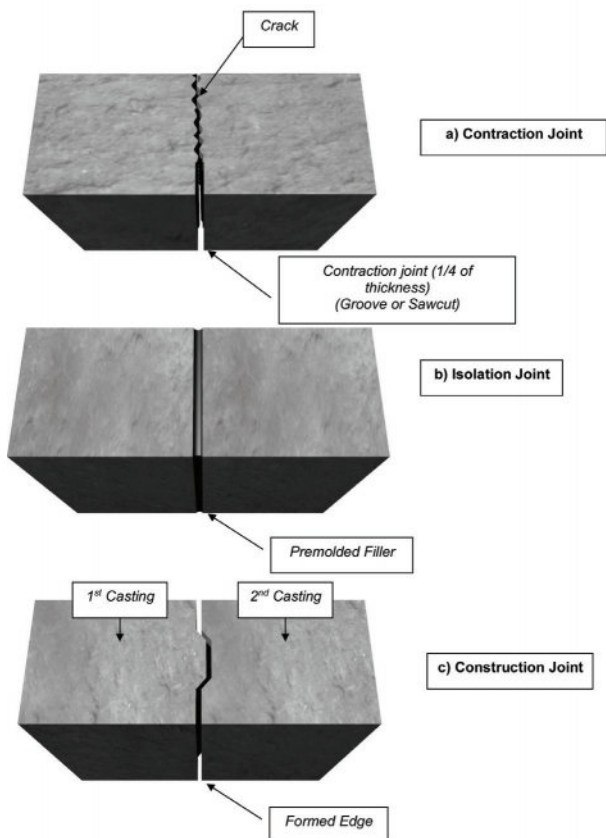


Fig. 2.2.9—Air-entrained concrete is highly resistant to repeated freezing-and-thawing cycles versus non-air-entrained concrete.

do not. This shrinks the top layer and can cause wide, shallow cracks.



Drying shrinkage is unavoidable in normal concrete; therefore, designers use properly sized and spaced reinforcing steel to reduce the size of cracks, and movement joints are used to control the location of shrinkage cracks. Concrete volume changes caused by fluctuations in temperature can also cause internal stresses and cracking, particularly at an early age.

Besides early curing, movement joints are the most effective method of controlling the location of cracking (Fig. 2.2.13). If a sizable expanse of concrete (a wall or a slab) is not provided with properly spaced movement joints to accommodate drying shrinkage and temperature changes, the concrete will still shrink and cracks will form at random locations to relieve the internal stresses.

Fig. 2.2.13—Top view of three basic types of joints used in concrete construction.

- (a) Contraction joints are grooved, formed, or sawed into sidewalks, driveways, pavements, floors, and walls so that cracking will occur in these joints rather than in a random manner. Contraction joints permit movement in the plane of a slab or a wall. They usually extend to a depth of approximately one-quarter the concrete thickness. Engineers will often terminate all or a portion of the reinforcing at a movement joint to substantially weaken the joint and attract cracking to that location. If contraction joints are sawed into the concrete after hardening, care should be taken to not cut the reinforcing steel that is close to the surface.
- (b) Isolation joints separate an element from other parts of a structure and permit horizontal and vertical movements. For example, they are placed at the junction of a slab with walls, columns, footing and other points where restraint can occur. They extend the full depth of the slab and include a joint filler.
- (c) Construction joints occur where concrete work is concluded for the day. They separate areas of concrete placed at different times. Construction joints usually align with and function as control or isolation joints.

CHAPTER 3—CONCRETE MATERIALS

This chapter describes the principal ingredients that make up the concrete mixture:

- a) Cement
- b) Fine aggregate
- c) Coarse aggregate
- d) Water
- e) Chemical admixtures
- f) Supplemental cementitious materials

The quality of these principal ingredients, their proportions, and the way they are mixed all affect strength and other properties of the concrete. Shotcrete may also contain fibers of steel, polypropylene, and other materials.

3.1—Cements

Many types of cement are available in today's concrete industry and the most currently used ones are described in the following sections. Cements made by different producers are unique and respond differently to admixtures.

3.1.1 Portland cements

Portland cements are hydraulic cements, which means they set and harden by reacting chemically with water. During the chemical reaction, called hydration, the reaction produces heat as it forms a stone-like mass that binds the aggregate particles together. Eighty to 85 percent of concrete's hydration and ultimate strength gain takes place in the first month (typically referred to as 28 days). After that, there may be slow gains in strength over long periods if moisture is available.

Type I portland cement is usually carried in stock and is supplied when the cement type is not specified. Type II is also widely available, particularly in areas with saltwater exposure or moderate sulfate content in the soil. Together, Types I and II make up 90 percent of the cement shipped from U.S. plants. Many cement manufacturers produce cements that meet both the Type I and Type II chemical composition requirements and are referred to as a Type I/II cement.

The selection of a specific cement for a project is usually based on the required early strength development or on the limitation of the heat of hydration generated. Therefore, when early strength is required, a Type III cement should be selected because of its faster early strength development. If the heat of hydration is a concern, however, such as massive applications (for example dams or raft foundations),



a Type II or IV would be preferred because they develop strength at a slower rate, which as a result reduces the heat generated. In mass concrete, control of heat generated during hydration is important to limit undesirable thermal stresses and subsequent cracking. Descriptions of each type of portland cement are listed in the following sections.

3.1.1.1 Type I, normal cement

It is a general-purpose cement used where the special properties of the other types are not required. It is widely used in slabs-on-grade, reinforced concrete buildings, bridges, and elsewhere where the concrete is not exposed to aggressive environments or to detrimental temperature rise due to heat of hydration.

3.1.1.2 Type II, moderate sulfate resistance

It is used in wastewater structures and coastal or marine areas where moderate sulfate exposure must be resisted. It usually generates heat of hydration more slowly than Type I and gains strength more slowly than Types I and III, but eventually catches up (approximately 56 days) if concrete is properly cured.

3.1.1.3 Type III, high early strength cement

It is like Type I, but more finely ground, so that it develops strength faster. It usually develops in a week or less the same strength that Type I would give at 28 days. Generally, it generates heat of hydration faster, and more shrinkage can be expected because it requires more water in the concrete mixture. It is useful when forms need to be removed early or a structure must be put into service quickly.

3.1.1.4 Type IV, low heat of hydration

It develops strength at slower rate than other types and releases less heat as it hydrates. Type IV cement is no longer manufactured in the U.S. because supplemental cementitious materials offer a less expensive way to control temperature rise.

3.1.1.5 Type V, high sulfate resistance

It is used in concrete exposed to severe sulfate exposure. This can occur where soils or ground water have a high sulfate content. It can also be an issue in wastewater collection and treatment facilities. Sulfate attack can cause major deterioration in concrete. Using Type V cement increases the resistance to sulfate attack.

3.1.1.6 White portland cement

It differs from regular cements chiefly in color, but usually conforms to Type I or Type III standards. White portland cement is used primarily for architectural purposes in both precast and poured concrete. It is necessary for white concrete, and gives brighter, more intense colors for colored concrete in which pigments are added during the mixing.

3.1.2 Special cements

A small portion of the U.S. cement production goes into special hydraulic cements. There are five classes of blended hydraulic cements for both general and special applications. They are produced by blending two or more fine materials from the following list:

- a) Portland cement
- b) Silica fume
- c) Fly ash
- d) Slag
- e) Metakaolin

3.1.3 Calcium aluminate cement (CAC)

Calcium aluminate cement does not contain portland cement. It is used in special applications when very early strength gain and resistance to chemical attack and high temperatures are required. Combinations of portland cement and calcium aluminate cement have been used to make rapid setting concretes and mortars. Typical applications for calcium aluminate cement concrete include: chemical-, heat-, and corrosion-resistant industrial floors; acid-resistant linings in sewers and treatment plants; refractory castables; and repair applications.

3.2—Supplementary cementitious materials (pozzolans)

Finely divided supplemental cementitious materials are used in relatively large amounts, generally replacing 10 to 50 percent of the portland cement in a concrete mixture design. They are powdered or pulverized materials added before or during mixing to improve or change the properties of concrete. The pozzolans are generally natural or by-product materials such as:

- a) Silica fume
- b) Fly ash and natural pozzolans
- c) Metakaolin
- d) Slag

Some of these minerals, such as slag, have cementitious properties; that is, they can set and harden in the presence of water. The pozzolans by definition are materials that have

little cementitious action when used alone, but when used with portland cement, they react with products of cement hydration to develop additional cementing action. Some of the finely divided minerals have both cementitious and pozzolanic properties.

The most commonly used pozzolans in shotcrete are silica fume and fly ash. Undensified silica fume, sometimes called microsilica, is a pozzolan with particles only one hundredth the size of cement particles. Silica fume is a very fine noncrystalline silica produced in electric arc furnaces as a byproduct of the production of elemental silicon or alloys containing silicon.

Fly ash is a finely divided residue that results from burning ground or powdered coal as in coal-burning power plants. Fly ash particles are spheres with a diameter similar to that of portland cement particles. In addition to improving hardened properties of concrete, silica fume and fly ash are commonly used to improve the plastic properties of the fresh shotcrete.

Most pozzolans reduce the permeability of concrete by filling in the spaces between cement particles, thus improving durability. In the amounts normally used, some pozzolans cause a reduction of early strengths up to 28 days but improve the long-term strength. Because some pozzolans react slowly, longer curing and protection of the surface from freezing or contact with aggressive substances are often recommended for concrete containing pozzolans.

3.3—Aggregates

The sand, gravel and crushed stone that are mixed with cement and water to make concrete are called aggregates. Aggregates make up 70 to 80 percent of concrete by weight. A cubic yard (yd^3) of normal weight concrete may contain 2800 to 3200 lb of aggregates (a cubic meter [m^3] of normal weight concrete may contain 1600 to 1800 kg of aggregates). This distribution is shown in Fig. 2.1.2b.

Concrete that is made without coarse aggregate is usually called mortar or grout. Most concrete used in building construction has a maximum aggregate size from 3/8 to 1-1/2 in. (10 to 40 mm). In massive concrete structures like dams and mat foundations, large aggregate sizes of 6 in. (150 mm) or more are often used.

Natural gravel and sand usually are taken from a pit, river, lake, or seabed. Aggregates from saltwater areas should not be used unless specially processed because of problems with seashells and salt content. Crushed aggregate can be made from natural gravel, quarry rock, cobbles, or boulders.

ders. Whether the aggregate is crushed or natural, the mix of aggregate sizes is not always ideal for making concrete. The aggregate producer may combine aggregates of various sizes to meet the proportions required in standard specifications.

Normalweight aggregates should meet minimum quality standards. A number of standardized tests (usually from ASTM) can be used to determine if an aggregate is acceptable and will produce strong, durable concrete. Some important aggregate properties that affect the quality of the concrete are:

- a) Maximum nominal size
- b) Aggregate size distribution
- c) Aggregate shape
- d) Hardness
- e) Moisture in the aggregate
- f) Amount of coarse and fine aggregate in the mixture
- g) Potential for alkali-silica reactivity
- h) Sulfate resistance

3.3.1 Maximum size of aggregate

The largest aggregate that can be used can depend on the size and shape of the member to be made of the concrete. The selection of the size of large aggregate is also affected by the spacing and location of embedded reinforcing steel and equipment limitations such as the size of concrete pumps and hose diameter. Concrete designers generally select the largest economical aggregate available that meets the limitations because a larger aggregate size helps to reduce the cement paste required in the mixture and resultant drying shrinkage potential.

3.3.2 Aggregate gradation (size distribution)

Aggregates are made up of particles of many different sizes. To make concrete batches that are consistent, the total quantity of aggregate and the distribution of particle sizes should be essentially the same from batch to batch. To measure the distribution of aggregate sizes in a given sample, the dry aggregate particles are passed through a number of standardized sieves (screen/meshes of varying opening sizes) starting with the largest openings and using smaller and smaller openings in successive sieves. The aggregate size distribution (gradation), can then be calculated by the weight retained on each size sieve.

There are several reasons for specifying gradation criteria and maximum aggregate sizes. The amount of cement paste needed for a workable mixture depends on the aggregate size. For example, with 1 in. (25 mm) maximum size aggregate,

less cement and water are needed to produce concrete with a given strength than with 1/2 in. (12 mm) aggregate. Workability, porosity, resistance to degradation from freezing and thawing, pumpability, and other properties can be affected by the gradation and aggregate size. Variations in gradation can cause pumping problems and can also seriously affect the uniformity of concrete from one batch to the next. In general, aggregates that have relatively equal amounts of aggregate retained on each of the sieves will produce the best results. These aggregates are said to have a smooth grading curve or a well-graded distribution (Fig. 3.3.2(a)).

Concrete with a well-graded aggregate distribution (Fig. 3.3.2(a)) will have a smaller total volume of voids between aggregate particles that should be filled with cement paste. This provides a desirable and efficient use of cement paste.

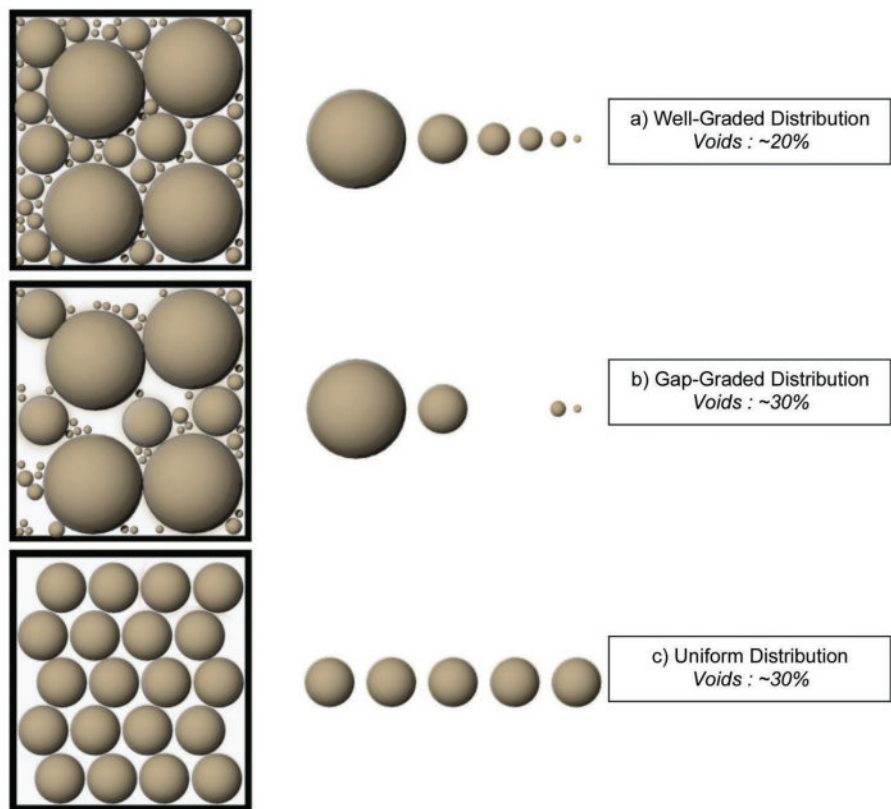


Fig. 3.3.2—Illustration of different aggregate size distributions: (a) well-graded distribution; (b) gap-graded distribution; and (c) uniform distribution.