



American Concrete Institute®

CRAFTSMAN WORKBOOK

ACI Certification Program for Shotcrete Nozzleman

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CRAFTSMAN WORKBOOK

Foreword

Shotcrete is receiving more attention and use in the construction industry. Because of this, the need for knowledgeable qualified craftsmen is also increasing. One way of verifying a shotcrete nozzleman's basic knowledge and skills is through a certification program.

The American Concrete Institute (ACI) provides leadership in the industry by administering certification programs for concrete construction personnel. ACI's position and reputation as an established and independent group of acknowledged concrete experts—and in this case, shotcrete experts—enables it to effectively operate a nationally-recognized certification program.

This workbook is essential to nozzle men wishing to achieve “ACI Certified Shotcrete Nozzleman” status. It contains all the reference material necessary for the nozzleman to study for

the knowledge aspect of becoming certified. At the end of each text chapter are sample study questions to help examinees verify that they understand the material presented. This should also help craftsmen who may not be accustomed to taking examinations to be mentally prepared for the written exam.

In addition, this workbook contains a description of the performance evaluation component of the certification process. The performance evaluation consists of three parts: (1) oral review of key aspects with the examinee by an examiner, (2) examinee shooting a test panel, and (3) evaluation by the examiner of cores removed (through reinforcing steel) from the test panel. Successful completion results in each examinee receiving a certificate and a wallet card indicating in which process(es) and position(s) they are certified.

Check the ACI website for updated information and/or errata/addendums:
www.concrete.org/certification/cert_errata.htm

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PROGRAM INFORMATION

PURPOSE AND IMPORTANCE OF ACI CERTIFICATION

Certification as Shotcrete Nozzleman through the ACI provides a technician with international recognition by an independent group of acknowledged concrete experts. This recognition may improve the technician's potential for advancement and employment opportunities.

The nozzleman is one key element to quality in the shotcrete process. Through the certification process, the nozzleman demonstrates his/her knowledge and skill. This also results in better understanding of concrete, the shotcrete process, and the elements of a quality end product. Thus, everyone involved in a shotcrete project benefits. The owner gets a better quality product, the designer has greater assurance that specification requirements are being met, and the shotcrete contractor gets positive referrals for more work.

PROGRAM OVERVIEW

The ACI Certification Program for Shotcrete Nozzleman consists of:

- 500 hours of verified work experience as a nozzleman or nozzleman-in-training
- A passing grade on the written examination
- Successful completion of a two-part performance evaluation as follows:
 - Part I – Demonstration of knowledge of all the items covered on the Performance Checklist; and
 - Part II – Shooting a test panel with the method(s) and position(s) to be certified.

The test panel will be cored and evaluated.

Both the written examination and the performance evaluation are based on "Shotcrete for the Craftsman", ACI Publication CCS-4. The examinations require a working knowledge of concrete/shotcrete construction, including:

1. Basic Concrete Technology
2. Shotcrete methods, uses, materials and equipment
3. Preparation before shooting
4. Placing techniques
5. Finishing, curing and protection
6. Safety
7. Testing/Quality

The Local sponsoring group is not required to conduct a training course prior to the examinations. Bypassing a formal training course and following a course of self-study is generally discouraged, but it

is not precluded. When a training course is not offered in conjunction with the examinations, alternative methods of preparation are necessary and should be formulated by all parties involved, such as the examinees, their employers, and the local sponsoring group.

ADMINISTRATION

ACI, through its Certification Programs Committee, administers the certification program. This includes the development and maintenance of all program policies and procedures, instructional materials, and examinations.

The ACI certification program is conducted by a local sponsoring group, such as an ACI chapter, a state or local concrete industry association, a college or university, or an other organization committed to upgrading the quality of concrete. This group is responsible for scheduling and conducting all examination sessions (and may offer optional training courses); arrangement of facilities, materials, equipment, and personnel; payment of all bills; and establishment and collection of all registration fees.

The ACI Certification Department assists the local sponsoring groups in setting up the program and manages the daily operation of the program. This includes the publication and dissemination of all instructional materials and examinations, grading examinations, maintenance of certification records, and issuance of certification to successful candidates.

DEFINITIONS

ACI — The American Concrete Institute (PO Box 9094, Farmington Hills, MI 48333-9094), which developed and published the instructional materials and examinations used in this program, and which certifies individuals who satisfy all requirements of this program.

ACI Certification — A formal recognition, valid for a specified period of time, which shows that a person has satisfactorily completed the certification requirements.

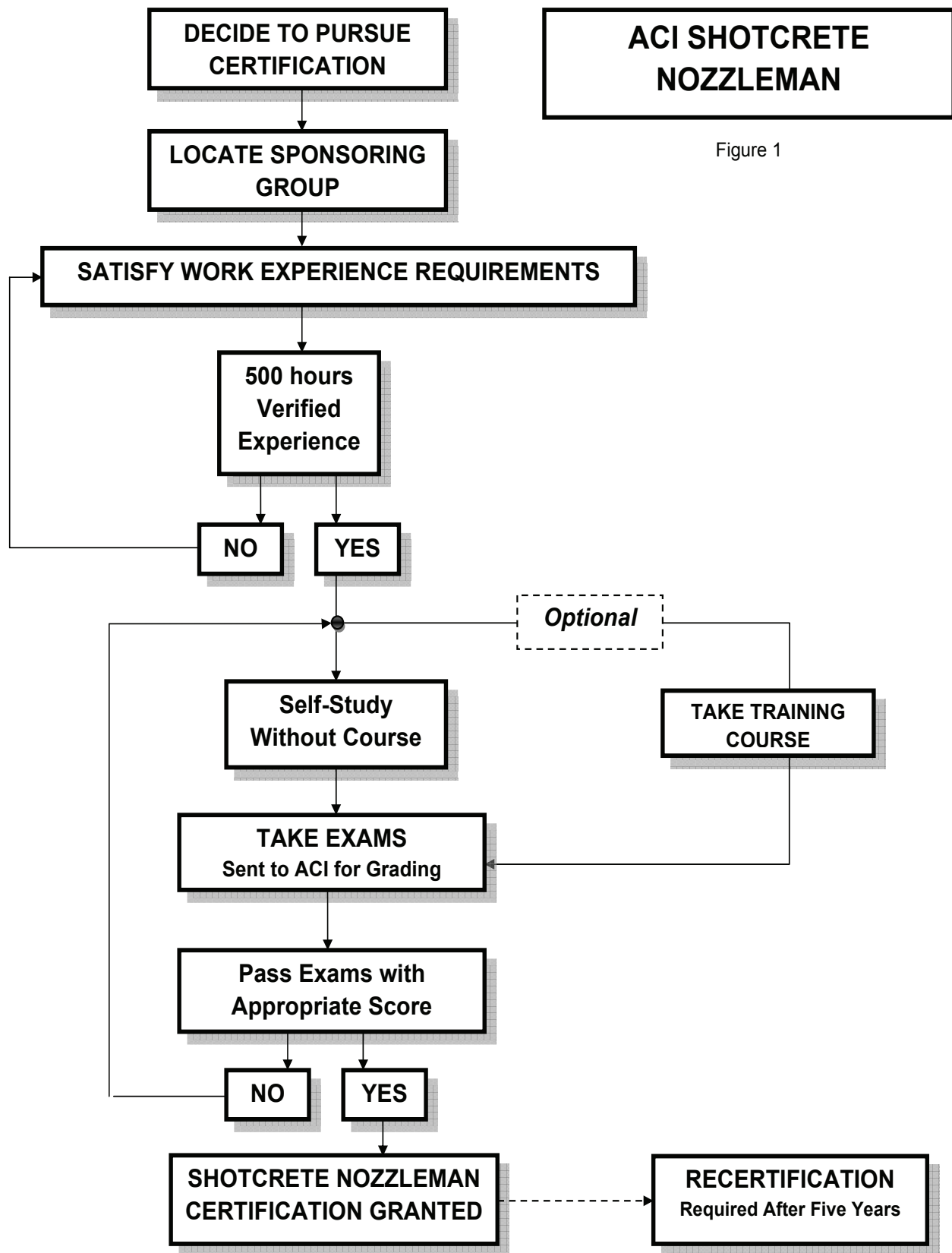
ACI Certification Department — The department within ACI that manages the certification programs.

Examiner — An individual knowledgeable in shotcrete, meeting criteria set forth in ACI's Shotcrete Nozzleman Certification Policies Document, approved by ACI and authorized to administer the examination sessions locally.

Examinee — A person applying for examination to become a certified shotcrete nozzleman.

Local Sponsoring Group — The local organization (such as an ACI chapter, state or local





concrete trade association, college or university, public agency, private testing laboratory, or other organization), that takes responsibility for conducting the certification examinations in its locality and, as a recommended option, for conducting a training course.

Proctor – A person chosen by the examiner to assist in conducting the written exam.

Recertification — A process undertaken prior to expiration of original certification by which a certified individual renews certification by successfully completing the then-current recertification requirements.

Shotcrete Nozzleman – The worker on a shotcrete crew who manipulates the nozzle, controls the material's consistency (dry process), and controls the final placement of the material.

Shotcrete Nozzleman-in-Training – An individual who has worked at least 500 hours operating a nozzle under the direct supervision of an experienced or certified Nozzleman.

Supplemental Examiner — An individual knowledgeable in shotcrete, meeting criteria set forth in ACI's Shotcrete Nozzleman Certification Policies Document, approved by the examiner to assist in administering the performance exam.

EDUCATIONAL MATERIALS

The Craftsman Workbook is the primary study resource and contains the essential resource material you need to prepare for the examinations. All the material for the certification is derived from "Shotcrete for the Craftsman", ACI publication CCS-4.

If a question should arise concerning the educational materials used in this program, please contact the ACI Certification Department for clarification.

PREPARATION FOR THE EXAMS

ACI recommends that you attend a training course prior to the examinations if offered by the local sponsoring group. Local sponsoring groups typically have access to resources (laboratory equipment and time, training videos, etc.) that an individual does not. Course content and instructional time varies between local sponsoring groups depending on local needs.

If a training course is not offered, or if you choose not to enroll in the course when offered (not recommended), a course of self-study should be planned.

QUALIFICATIONS OF EXAMINEES

This is a formal certification program, and as such, is NOT designed as a training program. Thus, applicant examinees are expected to be experienced and thoroughly familiar with the "tools of the trade." Shotcrete involves high-pressure equipment and

materials projected at high velocity. Safety considerations are of the highest priority; this is in part why ACI requires an applicant to submit documentation reflecting 500 hours of work experience for verification as a nozzleman or nozzleman-in-training prior to allowing further participation in the certification process.

RESPONSIBILITIES OF TRAINEES/EXAMINEES

To become certified, examinees have the responsibility for following this procedure:

1. Locate a local sponsoring group and obtain the application and registration forms;
2. Complete the following forms and submit them to the local sponsoring group:
 - a. Program Registration;
 - b. Examinee Application Form; and
 - c. Work Experience Affidavit.

Note: 500 hours of verified work experience as a nozzleman or nozzleman-in-training is required to sit for the exam

3. Obtain from the Local sponsoring group or ACI a copy of this Workbook or a copy of "Shotcrete for the Craftsman", ACI publication CCS-4;
4. Take the optional training course (if offered) or establish a course of self-study; and
5. Appear for the written and performance examinations.

TRAINING COURSE

Local sponsoring groups may or may not offer a training course in conjunction with the examination sessions. If a training course is not offered in your area or if you choose not to enroll in the course when offered (not recommended), you should plan a course of self-study. Included in this workbook are materials and references that you will find useful for this program.

Remember that your individual study, with or without the training course, can mean the difference between passing and failing the ACI examinations.

WRITTEN EXAMINATION

In addition to work experience and performance evaluation requirements, certification as a nozzleman requires passing a closed-book written examination. There are separate examinations for wet-mix and dry-mix, each consisting of 60 to 90 questions ranging from concrete basics to process specifics. The passing grade for each exam is 75%.

Different versions of the examinations, all equally difficult, are compiled from a large collection of questions and answers submitted by members of ACI Committee C660, Shotcrete Nozzleman Certification. The examination version is changed on a regular basis for reasons of security and fairness.

PERFORMANCE EXAMINATION

Performance examination positions currently available are:

Process:	Position:
Wet-Mix (structural)	Vertical (mandatory) Overhead (optional)
Dry-Mix (structural)	Vertical (mandatory) Overhead (optional)

Note that not all local sponsoring groups and test sites are equipped to perform all the aforementioned options. You should verify with your local sponsoring group that the options you want are available.

All examinees are required to take the vertical panel performance examination; certification in the overhead position, if pursued, is contingent upon passing the vertical position.

The shotcrete mixture to be shot will be a mixture in common use in the geographic area of the test site. The mixture for the wet-mix process may be a locally supplied ready mix or dry materials wet-mixed at the test site. Dry-mix may be prepackaged materials or bulk materials dry-batched at the test site. Mixtures may contain accelerators, and may not contain other admixtures. If you have any questions as to the mixture to be used, you should contact the local sponsoring group at least 1 week before the test.

Similarly, equipment available at different test sites may vary. You should contact the local sponsoring group to find out what equipment will be used for the test.

You are required to provide your own personal protection equipment (hard hat, safety glasses, respirator/dust mask, and protective clothing).

The performance examination requires that you demonstrate your knowledge of surface preparation, equipment, start-up procedures, proper placing/nozzling technique, and finishing and curing. An examiner or supplemental examiner will witness your work and use a performance checklist to evaluate your performance. In the event of an equipment malfunction during shooting of a test panel, you may wash out the panel and start over. After your test panel has gained sufficient strength, it will be cored. Cores taken through reinforcing steel will be evaluated visually for quality (number and size of voids and/or sand lenses and encasement of the reinforcing steel).

The overall performance examination grade is derived from the following two parts:

Part I: The score achieved on the performance checklist, including workmanship technique; and

Part II: The score achieved on the cores removed from the test panel(s).

To be certified in the positions and processes

you are pursuing, you must pass both parts of the performance examination as described previously for each panel position in each process pursued. The overall passing grade is 75% or higher.

Test panel details are shown in Appendix C.

AMERICANS WITH DISABILITIES ACT (ADA)

If you have a disability and require special accommodations, please contact ACI Headquarters for further information on how to proceed. All requests for special accommodations under ADA are handled on a case-by-case basis and must be made allowing enough time for evaluation and appropriate action by ACI.

REEXAMINATION

In the event of a failure, it is your responsibility to request a reexamination. To do so, you must contact the local sponsoring group and arrange for a convenient time, location and the appropriate fee. If further assistance is required, you may contact the ACI Certification Department.

Failure of the written examination by either of the criteria cited under WRITTEN EXAMINATION requires reexamination on the entire written examination. The written examination must be passed within one (1) year of passing the performance examination.

Failure of either Part I or Part II of the performance examination by any of the criteria cited under PERFORMANCE EXAMINATION will require reexamination of the entire performance exam. Reexamination must be completed within one (1) year of passing the written examination. Reexamination on the same day as the original examination is permitted at the discretion of the examiner and is subject to scheduling constraints and materials availability.

The performance examination for the vertical test panel must be passed for certification to be issued. If you pursue certification in the overhead position and fail the performance exam for the vertical position, you must retake the entire performance exam, including the performance exam for the overhead panel.

It is your responsibility to request a reexamination. To do so, contact either the examiner and/or the local sponsoring group to arrange a convenient time, location and appropriate fee. If you require further assistance, contact the ACI Certification Department.

APPEALS

All ACI certification policies, procedures, requirements, and examination materials have been developed through the voluntary consensus process and then carefully reviewed for accuracy and fairness. However, an appeal process is available for you in

the event you feel that some aspect of the examination is unclear, incorrect, or unfair. If your complaint is found to be valid, ACI will adjust the examination grades accordingly.

The first level of appeal rests with the examiner. This person is a registered professional engineer with sufficient education and experience in concrete testing and inspection to be approved by ACI as their local representative for this program.

If the examiner cannot satisfy your complaint, appeals are handled in order by the following entities:

1. Local sponsoring group
2. Director of Certification
3. Certification Appeals Committee
4. Committee C660, Shotcrete Nozzleman Certification
5. Certification Programs Committee

Note: Members of the Certification Appeals Committee include the Managing Director of Certification, the Chair of the Certification Programs Committee, and the Chair of Committee C660.

All questions for the written examination are developed through ACI Committee C660, Shotcrete Nozzleman Certification, and maintained at ACI Headquarters by the ACI Certification Department. Neither the examiner nor the local sponsoring group has any jurisdiction over the content or the scoring of the written examination. While the examiner or proctors may offer advice, they are not responsible for the explanation or interpretation of any examination question.

If you encounter a test question that appears to be unclear, incorrect, or unfair, please describe your complaint on an ACI Challenge Form (found in the

test booklet). If you do not use an official Challenge Form, your appeal will still be considered as long as it is submitted (in writing) to the ACI Certification Department at ACI Headquarters within 60 days of receipt of the examination.

The checklists used on the performance examination were also developed through ACI Committee C660, Shotcrete Nozzleman Certification. Consequently, they cannot be altered by the examiner or the local sponsoring group. However, since the performance examination is slightly more subjective in nature than the written examination, the examiner or supplemental examiners do have the authority to interpret some of the procedures.

If you feel that your performance has been incorrectly or unfairly evaluated, please explain your complaint to the examiner. If you are not satisfied with the examiner's decision, you may continue to appeal your case. All verbal appeals should be confirmed in writing to the local sponsoring group and to the ACI Certification Department at ACI Headquarters within 60 days of receipt of the examination.

RECERTIFICATION

Your ACI certification as a Shotcrete Nozzleman expires in five (5) years, unless you become recertified. Recertification is a process that extends your certification for another five (5) year period from the date of successful completion of the recertification requirements. Recertification requires successful completion of both the written and performance examinations.

SECTION 1

CCS-4 Chapter 1 What the Shotcrete Craftsman Should Know About Concrete

- 1.1—What is Concrete?
- 1.2—Fundamentals of Concrete
 - 1.2.1—Freshly-Mixed Concrete
 - 1.2.2—Workability
 - 1.2.3—Consolidation
 - 1.2.4—Hydration, Setting Time, and Hardening
 - 1.2.5—Curing
 - 1.2.6—Drying of Concrete
 - 1.2.7—Strength
 - 1.2.8—Unit Weight (Density)
 - 1.2.9—Resistance to Freezing and Thawing
 - 1.2.10—Permeability and Impermeability
 - 1.2.11—Abrasion Resistance
 - 1.2.12—Shrinkage
 - 1.2.13—Control of Cracking

CHAPTER 1—WHAT THE SHOTCRETE CRAFTSMAN SHOULD KNOW ABOUT CONCRETE

It seems logical to expect that the craftsman should know the basics of concrete. A shotcrete craftsman should know what concrete is made of and how it behaves. Shotcrete workers should know the basic properties of concrete and 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 will help workers to produce better concrete. Most of this manual deals with shotcrete use, but many of the principles discussed also apply to other types of concrete work.

As such, Chapter 1 of this workbook is an overview of plastic and hardened concrete properties in

general. Chapter 2 describes various key ingredients of concrete mixtures and Chapter 3 presents general mixture proportions. Chapters 4 to 12 pertain to shotcrete technology and include topics such as materials, equipment, preparation before shooting, placement, principles and techniques, communication, environmental conditions and precautions, finishing and tolerance controls, safety, and testing/quality.

1.1—What is Concrete?

Concrete is the most widely used construction material today. Worldwide, approximately 1 ton is produced every year for every living human being. This happens because concrete is the least costly, most readily-available construction material. Fortunately, it 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 and other properties that the designer specified when the work was planned. Much of this concrete quality depends directly on the workers in the field. Because they work with it, they should understand some important factors affecting the properties of concrete.

Concrete is a mixture of two components: aggregate and paste. The paste is made of portland cement and water, and acts as the glue that binds the aggregates (sand and gravel or crushed stone) into a rock-like mass as the paste hardens, due to the chemical reaction of the cement and water (Fig. 1.1).

The term cement used throughout this section refers to portland cement unless otherwise stated (see Section 2.1). People sometimes refer to the mixture of cement, water, and aggregates as cement, but this is technically wrong; it is concrete. Only the binding powder is properly called cement.

Aggregates are usually divided into two groups: fine and coarse. Fine aggregates consist of natural or manufactured sand with particle sizes ranging up to 5 mm (1/4 in.); coarse aggregates are those with most particles retained on the 5 mm sieve (1/4 in.) and ranging up to 150 mm (6 in.). The most commonly used maximum aggregate size in concrete is 20 to 40 mm (3/4 to 1.5 in.) (see Section 2.3).

Paste comprises portland cement, water, and entrapped air or purposely entrained air. Cement paste ordinarily constitutes approximately 20 to 30% of the total weight of concrete. Figure 1.2 shows that the total weight of cement is usually between 13 and 20% and the water between 7 and 10% in a typical concrete mixture. The air content in air-entrained

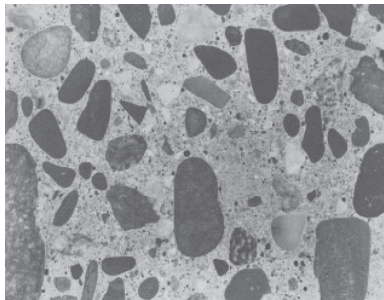


Fig. 1.1—Polished section sawed from concrete. The cement-and-water paste coats each piece of aggregate and fills all spaces between aggregate particles (photo courtesy of the Portland Cement Association).

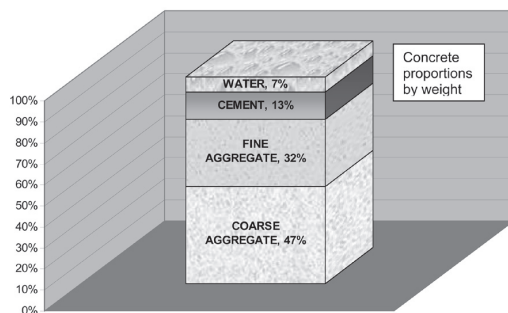


Fig. 1.2—Proportions by weight of materials in typical concrete mixture, freshly mixed. In other mixtures, total aggregate may range by weight from 70 to 80% and cement from 13 to 20%. Typical shotcrete mixture proportions by weight are presented in Table 3.1.

concrete ranges from approximately 3 to 8% of the volume of the concrete, depending on the maximum size of the coarse aggregate.

Because aggregates make up from approximately 70 to 80% of the total weight of concrete, their selection is important. Aggregates should consist of particles with adequate strength and resistance to exposure and should not contain materials that will cause deterioration of the concrete. A good gradation of particle sizes is desirable for efficient use of the cement and water paste. Chapter 2 provides further information on the description and properties of aggregates.

"The quality of the concrete depends to a great extent on the quality of the paste. In properly-made concrete, each particle of aggregate is completely coated with paste and all of the spaces between aggregate particles are completely filled with paste,"* as illustrated in Fig. 1.1. Chapter 2 also provides further information on the various types of portland cement.

"For any particular set of materials and conditions of curing, the quality of hardened concrete is determined by the amount of water used in relation to the amount of cement. The following are some advantages of reducing water content:

- Increased compressive strength and flexural strength;
- Lower permeability and absorption;
- Increased resistance to weathering;
- Better bond between successive layers and between concrete and reinforcement;
- Less volume change from wetting and drying; and
- Reduced tendency to crack due to shrinkage."*

In other words, "the less water used, the better the quality of the concrete—provided it can be consolidated properly."*

1.2—Fundamentals of Concrete

Concrete as described in this section means conventional concrete. Because shotcrete is concrete, this becomes essential information for the shotcrete craftsman and is further described in Chapters 4 to 13 in this document.

1.2.1—Freshly-Mixed Concrete

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

"In a plastic concrete mixture, all grains of sand and pieces of gravel or stone are encased and held in suspension [by the paste]. The ingredients are

not apt to segregate during transport; and when the concrete hardens, it becomes a [uniform] mixture of all the components."* Properly designed concrete of plastic consistency does not crumble but flows slowly without segregation.

Slump is used as a measure of the workability of concrete (Fig. 1.3). Slump measurement is a standardized test method that consists of placing a sample of fresh concrete and consolidating it by rodding in a cone-shaped mold. The mold is raised and the concrete allowed to subside. The vertical distance between the original and displaced, slumped position of the center of the top surface of the concrete is measured and reported as the slump of the concrete. A low-slump concrete has a stiff consistency, and the higher the slump, the wetter the mixture. In construction practice, thin concrete members and heavily-reinforced concrete members require higher slump (but never soupy) mixtures for ease of placement. A plastic mixture that does not segregate is required for maintaining homogeneity during handling and placement.

Whereas a plastic mixture is suitable for most concrete work, superplasticizing admixtures (see Section 2.5) may be used to make high-slump concrete that flows better in thin- or heavily-reinforced formed concrete members.

1.2.2—Workability

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

Excessive bleeding increases the [water content] near the top surface and a weak top layer with poor durability may result, particularly if finishing operations take place while bleeding water is present. Because of the tendency of freshly mixed concrete to segregate and bleed, it is important to transport and place each load as close as possible to its final position. Entrained air improves workability and reduces the tendency of freshly mixed concrete to segregate and bleed"* (see Section 1.2.10).

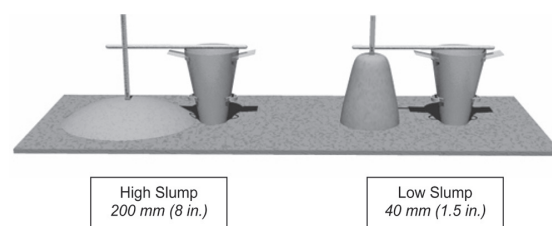


Fig. 1.3—Measure of workability of concrete (high slump versus low slump).

*APSP Builders Manual, second edition, National Spa & Pool Institute, Alexandria, VA, 2002, p. 7-3 to 7-5.

1.2.3—Consolidation

In conventional 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, harsher, as well as stiffer, mixtures can be used, resulting in improved quality and economy."* In the shotcrete process, which is the method described in Chapter 4, proper consolidation is achieved by compaction of the concrete when it is projected onto a surface at high velocity.

1.2.4—Hydration, Setting Time, and Hardening

The binding quality of portland cement paste is due to the chemical reaction between the cement and the water, called hydration, and its subsequent bond to aggregates. The product of this chemical reaction is hydrated cement paste, or more commonly called paste, which is referred to as the glue of the system.

The different chemicals making up cement react differently from one another. Some will react early and quickly, whereas 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 (see Section 2.1 for additional information).

Hardened cement paste forms dense, bonded aggregations that adhere to grains of sand and to pieces of 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 more durable the concrete. "When mixing concrete, therefore, 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 complete hydration of the cement.

"Knowledge of the amount of heat released as cement hydrates can be useful in planning construction. In winter, the heat of hydration may help protect [to a certain extent] the concrete against damage from freezing temperatures."* In the summer, the heat may be harmful, however, in massive structures such as dams because it may produce undesirable stresses in the concrete on cooling after hardening.

"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 must be slow enough to allow time for the concrete

to be transported, placed, [consolidated, and finished]."* Care must be taken in warm weather because the resulting higher mixture temperature may speed up the hydration reaction, thereby reducing the setting time and limiting the workability period of the concrete mixture. Other factors that influence the rate of hydration include temperature, amount of water added, cement type, and admixtures present in the mixture.

1.2.5—Curing

Because it is the reaction between water and cement, called hydration, that generates the glue 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 80% and the concrete temperature remains favorable. When the relative humidity within the concrete drops below approximately 80% or the temperature of the concrete drops below freezing, hydration and strength gain stop.

If concrete is resaturated after a drying period, however, 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 quality. Proper curing will also reduce the potential for the development of drying shrinkage cracks.

1.2.6—Drying of Concrete

Concrete does not harden by drying. As mentioned previously, concrete must continue to hold enough moisture throughout the curing period for the cement to hydrate. Freshly cast concrete has more water than needed just 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 80%. "A common illustration of this is the surface of a concrete floor that has not had sufficient moist curing. Because it has dried [too] quickly, concrete at the surface is weak and traffic on it creates 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 a primary cause of cracking, and the width and frequency of cracks is a function of the [rate] of drying. While the [exposed] surface of concrete will dry quite rapidly, it takes a much longer time for concrete in the interior to dry."* Thus, the "size and shape of a concrete member have an important bearing on the rate of drying. Concrete elements with a 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)."* Additional information is presented in Section 1.2.13, Control of Cracking.

*APSP *Builders Manual*, second edition, National Spa & Pool Institute, Alexandria, VA, 2002, p. 7-5, 7-7, 7-8.

1.2.7—Strength

The usual measure of strength of concrete is called compressive strength. It is expressed in MPa (mega-Pascal) or in psi (pounds per square inch) 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 100 mm (4 in.) in diameter and 200 mm (8 in.) long or 150 x 300 mm (6 x 12 in.), cast in molds at the time of placing concrete.

"Compressive strength of concrete is a primary physical property and one frequently used in design calculations for bridges, buildings, and other structures."* Most conventional concrete has a compressive strength in the range of 20 to 40 MPa (2900 to 5800 psi). Continuing advances in concrete technology are, however, making ever-higher strengths available. Regular good quality shotcretes have compressive strengths that typically range from 30 to 50 MPa (4500 to 7500 psi).

The strength of concrete is strongly affected by the amount of water and cement in the mixture (commonly called the water-cement ratio, which will be described further in Chapter 3), the age of the concrete, and the extent to which hydration has progressed.

1.2.8—Unit Weight (Density)

Conventional concrete, normally used in pavements, buildings, and other structures, weighs approximately 2350 kg/m³ (148 lb/ft³). Special heavyweight concretes, used in counterweights or radiation shielding weigh up to 3200 kg/m³ (200 lb/ft³). "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 water-and-cement content, which in turn are 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 2350 kg/m³ (148 lb/ft³).

1.2.9—Resistance to Freezing and Thawing

Concrete used in structures, pavements, or tunnels is expected to have long life and low maintenance. It must 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, as shown in Fig. 1.4. During freezing, the water expands and is displaced by ice in the paste; the air bubbles in the paste provide chambers for the water to enter and thus relieve the hydraulic pressure generated. Deterioration occurs when the water cannot escape fast enough (the pressure generated exceeds the tensile strength of concrete), causing internal cracking and/or surface scaling (see Section 2.5.5 for additional information).

Air-entrained concrete is much more resistant to damage from freezing-and-thawing cycles than non-air-entrained concrete and concrete with a low water-cement ratio (w/c) (see Chapter 3) is more durable than concrete with a high w/c .

1.2.10—Permeability and Impermeability

"Concrete used in water-retaining structures or exposed to weather or other severe exposure conditions must be as impermeable or watertight as possible. Impermeability is the ability of concrete to hold back or retain water without visible leakage. Permeability refers to the amount of water migration through concrete when the water is under pressure, or the ability of concrete to resist penetration of water or other substances (liquid, gas, and ions). Generally, the same properties of concrete that make concrete less permeable also make it more watertight."*

"A low w/c also reduces segregation and bleeding, further contributing to water tightness. To be watertight, concrete must also be free from cracks and honeycomb."*

1.2.11—Abrasion Resistance

Structures such as pavements, bridge decks, floors, and hydraulic structures are subjected to abrasion; therefore, in these applications, concrete must have high abrasion resistance. "Test results

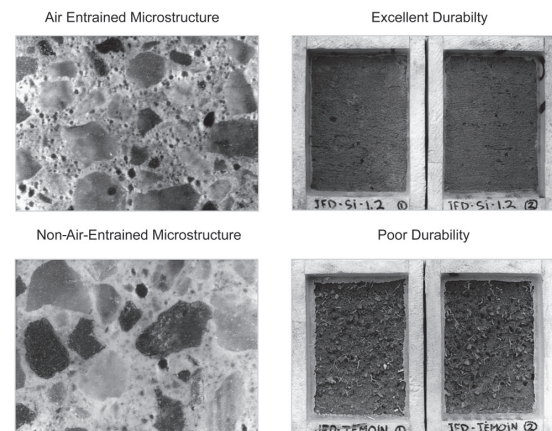


Fig. 1.4—Air-entrained concrete is highly resistant to repeated freezing-and-thawing cycles versus non-air-entrained concrete.

*APSP Builders Manual, second edition, National Spa & Pool Institute, Alexandria, VA, 2002, p. 7-8, 7-9, 7-12.

indicate that abrasion resistance is closely related to the compressive strength of concrete [and the quality of aggregate used].”*

Because compressive strength depends on the w/c and curing, a low w/c and adequate curing are necessary for abrasion resistance. The types of aggregate and surface finish also have a strong influence on abrasion resistance. Hard aggregate is more abrasion resistant than soft aggregate, and a troweled surface resists abrasion more than a surface that is not troweled.*

1.2.12—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 water content of the freshly-mixed concrete. Drying shrinkage increases directly with increases in this 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.

1.2.13—Control of Cracking

The two primary causes of cracks in concrete are: 1) stress due to plastic/drying shrinkage or temperature changes in restrained conditions; and 2) stress due to applied loads.

Plastic shrinkage appears in the surface of fresh concrete soon after it is placed while it is still plastic and occurs when water evaporation is excessive.

Drying shrinkage is unavoidable in concrete; therefore, properly positioned reinforcing steel is used to reduce the size of cracks, and joints are used to control the location of cracks. “Thermal stress due to fluctuations in temperature can also cause cracking, particularly at an early age.”*

Besides early adequate curing, joints are the most effective method of controlling cracking (Fig. 1.5). “If a sizable expanse of concrete [a wall or a slab] is not provided with properly spaced joints to accommodate drying shrinkage and temperature contraction, the concrete will crack randomly.”*

*APSP Builders Manual, second edition, National Spa & Pool Institute, Alexandria, VA, 2002, p. 7-12, 7-13.

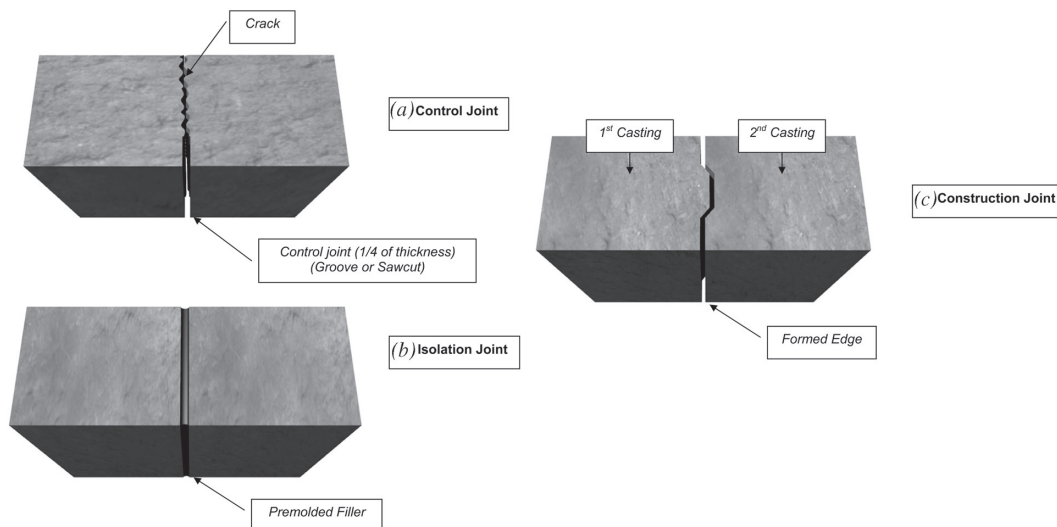


Fig. 1.5—Three basic types of joints used in concrete construction: (a) control joints are grooved, formed, or sawed into sidewalks, driveways, pavements, floors, and walls so that cracking will occur in joints rather than in random manner. Control joints permit movement in plane of slab or wall. They usually extend to depth of approximately one-quarter of concrete thickness; (b) isolation joints separate elements from other parts of structure and permit horizontal and vertical movements. For example, they are placed at junction of slab with walls, columns, footing, and other points where restraint can occur. They extend full depth of slab and include joint filler; and (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.

STUDY QUESTIONS

CCS-4 Chapter 1 What the Shotcrete Craftsman Should Know About Concrete

1. Concrete is a mixture of _____ and _____.
2. The term “paste” refers to the mixture of _____ and _____.
3. Aggregates make up _____ to _____ % of the weight of a concrete mixture.
4. The chemical reaction known as _____ causes concrete to harden.
5. Hydration is a chemical reaction between _____ and _____.
6. Conventional concrete has compressive strength in the range of _____ to _____ MPa (_____ to _____ psi).
7. The compressive strength of concrete is usually measured at a concrete age of _____.
8. Normalweight concrete weighs approximately _____ kg/m³ (lb/ft³).
9. Heavyweight concrete may weigh up to _____ kg/m³ (lb/ft³).
10. _____ shrinkage appears in the surface of fresh concrete soon after placement when water evaporation is excessive.

ANSWERS TO THE STUDY QUESTIONS ARE LOCATED IN APPENDIX A

SECTION 2

CCS-4 Chapter 2 Concrete Materials

- 2.1—Cements
 - 2.1.1—Portland Cements
 - 2.1.2—Types of Portland Cement
 - 2.1.3—Special Cements
 - 2.1.4—Calcium Aluminate Cement (CAC)
- 2.2—Supplementary Cementing Materials (Pozzolans).
- 2.3—Aggregates
 - 2.3.1—Maximum Size of Aggregate
 - 2.3.2—Aggregate Size Distribution
 - 2.3.3—Harmful Materials in Aggregate
- 2.4—Mixing Water
- 2.5—Admixtures
 - 2.5.1—Set-Accelerators
 - 2.5.2—Set-Retarders
 - 2.5.3—Water Reducers
 - 2.5.4—Superplasticizers and High-Range Water-Reducing Admixture
 - 2.5.5—Air-Entraining Admixtures

CHAPTER 2—CONCRETE MATERIALS

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

- Cement;
- Mineral additives;
- Fine aggregate;
- Coarse aggregate;
- Water; and
- Chemical admixtures.

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 reinforcing bars; welded wire fabric (wire mesh); or fibers of steel, polypropylene, and other materials.

2.1—Cements

Many types of cement are available in today's concrete industry and the most currently used ones are described in the following sections.

2.1.1—Portland Cements

Portland cements are hydraulic cements, which means they set and harden by reacting chemically with water. During the reaction, which is called hydration, they give off heat as they form a stone-like mass that binds the aggregate particles together. Most of the concrete's hydration and strength gain take 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.

2.1.2—Types of Portland Cement

The principal types of portland cement used in the U.S. are as follows.

Type I, normal cement—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 concrete is not exposed to aggressive environments or to objectionable temperature rise due to heat of hydration.

Type II, moderate sulfate resistance—Has limits on chemical composition. It is used in coastal or marine areas where deterioration from moderate sulfate exposure must be resisted, or in drainage structures where sulfate in groundwater is not unusually severe. Type II 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) when concrete is properly cured.

Type III, high early strength cement—Similar to Type I, but more finely ground, so that it develops strength faster. It usually develops in 1 week or less the strength that Type I would give at 28 days. It generally generates heat faster, and more shrinkage

can be expected because it requires more water per cubic yard. It is useful when forms need to be removed early or a structure must be put into service quickly.

Type IV, low heat of hydration—Develops strength at a slower rate than other types and releases less heat as it hydrates. Type IV cement is no longer manufactured in the U.S. because mineral additives (described later in this chapter as supplementary cementing materials) offer a less expensive way to control temperature rise.

Type V, high sulfate resistance—Used only in concrete exposed to severe sulfate action, principally where soils or groundwater have a high sulfate content. Sulfate attack can cause the concrete to crack and break up unless the concrete is made sulfate resistant.

White portland cement—White cement 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 cast-in-place concrete. It is necessary for white concrete, and gives brighter, more intense colors for colored concrete in which pigments are added during mixing.

The selection of specific cements 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 (dams), Type II or IV will be preferred, which are known to develop strength at a slower rate, and as a result, reduce the heat generated. Control of heat generated during hydration is important to limit undesirable stresses and subsequent cracking.

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% of the cement shipped from U.S. plants.

2.1.3—Special Cements

A small portion of the U.S. cement production goes into special hydraulic cements. Some of the more important types of special cement will be briefly described.

Blended 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:

- Portland cement;
- Silica fume;

- Fly ash;
- Ground-granulated blast-furnace slag; and
- Hydrated lime.

2.1.4—Calcium Aluminate Cement (CAC)

Calcium aluminate cement (CAC) is not portland cement-based. It is used in special applications when early strength gain and resistance to chemical attack and high temperatures are required. Portland cement and CAC combinations have been used to make rapid setting concretes and mortars. Typical applications for CAC concrete include chemically resistant, heat resistant, and corrosion resistant industrial floors; refractory castables; and repair applications.

2.2—Supplementary Cementing Materials (Pozzolans)

Finely divided mineral additives are used in relatively large amounts, generally replacing 10 to 50% of the portland cement. 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:

- Silica fume;
- Fly ash and natural pozzolans;
- Ground-granulated blast-furnace slags; and
- Hydraulic hydrated lime.

Some of these minerals such as the lime and ground slag have cement-like 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.

Today the most commonly used pozzolans in shotcrete are silica fume and fly ash. Condensed silica fume, sometimes called microsilica, is a pozzolan with particles only one-hundredth the size of cement particles. Silica fume is a by-product of the production of silica metal or alloys containing silica.

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, and also improve its durability. In the amounts normally used, most pozzolans cause a reduction of early strengths up to 28 days, but improve the long-term strength. Because pozzolans react slowly, longer curing and protection of the surface from freezing or contact with aggressive substances are often recommended for concrete containing pozzolans.

2.3—Aggregates

The sand, gravel, and crushed stone, which are mixed with cement and water to make concrete, are called aggregates. These materials make up 70 to 80% of concrete by weight. A cubic meter (m^3) of normalweight concrete may contain 1600 to 1800 kg (2600 to 3200 lb/yd³) of fine and coarse aggregates (Fig. 1.2).

Fine aggregate—If all of the particles are smaller than 5 mm (1/4 in.), the aggregate is called fine aggregate. Fine aggregates are either natural sand or manufactured sand produced by crushing rock.

Coarse aggregate—If most of the particles are larger than approximately 5 mm (1/4 in.), the aggregate is called coarse aggregate. It may be either gravel or crushed material. Gravel usually has smoothly rounded particles, while crushed stone has rough, angular surfaces. Some gravel pieces, however, may be crushed to size from large pieces of gravel.

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 20 to 40 mm (3/4 to 1-1/2 in.). In massive structures like dams and mat foundations, large

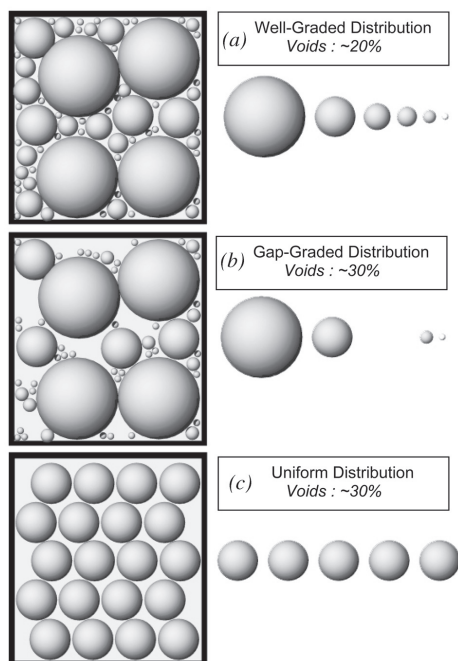


Fig. 2.1—Illustration of different aggregate size distributions: (a) well-graded distribution; (b) gap-graded distribution; and (c) uniform distribution.

aggregate sizes of 150 mm (6 in.) or more are often used.

Natural gravel and sand are usually taken from a pit, river, lake, or seabed. Aggregates from saltwater areas must not be used because of problems with seashells and salt content. Crushed aggregate can be made from natural gravel, quarry rock, cobbles, or boulders. Whether the aggregate is crushed or natural, the mixture of aggregate sizes is not always ideal for making concrete. The aggregate producer may pass aggregate over screens or sieves that sort out particles of various sizes, and then recombine them in proportions given in standard specifications.

Normalweight aggregates should meet minimum quality standards. A number of tests can be made to determine if an aggregate can be used to make strong durable concrete. Some important aggregate properties that affect the quality of the concrete are:

- Maximum size;
- Aggregate size distribution;
- Aggregate shape;
- Hardness;
- Moisture in the aggregate; and
- Amount of coarse and fine aggregate in the mixture.

2.3.1—Maximum Size of Aggregate

The largest aggregate that can be used depends on the size and shape of the member to be made of the concrete, and on the spacing and location of reinforcing steel in it, and sometimes can also be dictated by equipment limitations (concrete pumps, hose diameter, etc). Select the largest economical aggregate available that will meet these limitations because larger aggregate helps to reduce cement and water content of the mixture, thereby reducing shrinkage.

2.3.2—Aggregate Size Distribution

Aggregates are made up of particles of many different sizes. To enable making concrete batches that are essentially the same, the aggregate amount and distribution of particle sizes must be essentially the same from batch to batch. To measure the aggregate sizes, a dry sample of the aggregate is passed through a number of standardized sieves starting with the largest openings and using smaller and smaller openings in successive sieves. The aggregate size distribution, or grading, can then be defined precisely by the total weight passing each sieve.

There are several reasons for specifying grading limits and maximum aggregate sizes. The amount of cement and water needed for a workable mixture depends on the aggregate size. For example, with 25 mm (1 in.) maximum size aggregate, less cement and water are needed to produce concrete with a given strength than with 12.5 mm (1/2 in.) aggregate.

Workability, porosity, resistance to degradation from freezing and thawing, pumpability, and other properties can also be affected by the grading and aggregate size. In addition to causing pumping problems, variations in grading can also seriously affect the uniformity of concrete from one batch to the next. In general, aggregates that do not have a large deficiency or excess of aggregate passing 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. 2.1(a)).

As previously stated in Chapter 1 (Section 1.2.3, Consolidation), the larger the aggregate in concrete with a well-graded aggregate distribution, the less volume there is to fill with paste and the less aggregate surface area there is to coat with paste; thus less water and cement are needed. A continuous aggregate size distribution (or a smooth gradation) is desirable for efficient use of the cement and water paste (Fig. 2.1(a)). With adequate consolidation, harsher as well as stiffer mixtures can be used resulting in improved quality and economy.

A gap-graded aggregate size distribution (Fig. 2.1(b)), or a uniform distribution (Fig. 2.1(c)), however, will result in an increased volume of paste required to fill the voids. If the amount of paste is not sufficient, consolidation and/or pumping problems will occur.

2.3.3—Harmful Materials in Aggregate

Most specifications limit the amount of potentially harmful substances in aggregates. A primary concern is that poor aggregates will harm the durability of concrete. When more than 5% of a sand sample is too fine (diameter smaller than 80 μm [3.15 mil]), more water may be needed. Table 2.1 shows some harmful materials and the problems they may cause.

In addition to the items in Table 2.1, organic impurities may delay setting and hardening of concrete and reduce its strength gain. Many impurities can cause popouts, typically caused by freezing of moisture in unsound aggregates or excessive expansion of aggregate due to moisture gain.

Table 2.1—Most common harmful substances in aggregates

Item	Fine aggregate	Coarse aggregate
Clay lumps and friable particles	Unsound particles may affect durability and workability, cause popouts, and increase water demand of mixture	
Fine particles (< 80 μm [3.15 mil])	Affects bond of paste to aggregate and increases water demand	Can cause trouble when it exists as coating on coarse aggregate
Soft particles	—	Reduces durability and surface hardness

2.4—Mixing Water

Water quality is a concern because chemicals in it, even in very small amounts, sometimes change the setting time of the mixture or the long-term properties of the concrete. Almost any natural water that is drinkable can be used to make concrete. Some water that is not drinkable, including recycled water from mining and other industrial operations, may also be used, but tests should be made of such water before use.

Seawater may be not harmful to the strength of plain (unreinforced) concrete, but will cause reinforcement to rust in reinforced concrete. Water containing oil, salt, algae, or sugar should be checked before using in concrete.

2.5—Admixtures

Any material deliberately added before or during the mixing of concrete, other than cement, supplementary cementing materials, water, aggregates, and fiber reinforcement, is called an admixture. The freshly-mixed (plastic) and hardened properties of concrete may be changed by adding admixtures to the concrete, usually in liquid form, during batching. Admixtures are commonly used to: 1) adjust setting time or hardening; 2) reduce water demand; 3) increase workability; 4) intentionally entrain air; and 5) adjust other concrete properties. They are described as follows:

- Set accelerators;
- Set retarders;
- Water reducers;
- Superplasticizers (high-range water-reducing admixtures);
- Air-entraining agents; and
- Miscellaneous special purpose admixtures, such as color pigments, corrosion inhibitors, pumping aids, and latex modifiers.

2.5.1—Set-Accelerators

Accelerating admixtures speed up the setting and hardening of concrete. They can be useful in cold weather because concrete hardens slowly at low temperatures. In the past, the most common of these admixtures was calcium chloride. Calcium chloride in concrete, however, increases shrinkage and the potential for corrosion of reinforcing steel and some other metals. When required by the specifications, nonchloride accelerators are available for use.

2.5.2—Set-Retarders

Retarders slow down the setting time of the concrete. They are often used in warm weather to keep the concrete from setting before it can be placed and finished. Most retarders are also water reducers. They do not, however, prevent loss of slump over time.

2.5.3—Water Reducers

Water reducers, as the name suggests, reduce the

amount of water needed to produce a cubic meter (cubic yard) of concrete of a given slump. If they are put into a mixture without reducing the amount of water, water reducers will act to increase the slump of the concrete. Slump, as defined previously, is a measure of concrete's workability or consistency.

2.5.4—Superplasticizer and High-Range Water-Reducing Admixture

Superplasticizers or high-range water-reducing admixtures, reduce the water requirement for concrete dramatically. They can be used to temporarily increase the slump or workability of normal or stiff concrete to make it more flowable and easier to pump and to place. They can also be used to reduce the water needed while improving workability of concretes. The action of some high-range water-reducing admixtures lasts only approximately 30 to 60 minutes at normal temperatures; then the concrete stiffens very rapidly. For this reason, they are often added to the concrete at the job site. Extended-life high-range water-reducing admixtures are available for addition at the batch plant.

2.5.5—Air-Entraining Admixtures

Air-entraining admixtures create microscopic air bubbles in concrete. The bubbles are formed by the mixing action, and the air-entraining agents keep the bubbles from breaking up. Do not confuse entrained air with entrapped air, which consists of ordinary larger air spaces trapped in the concrete during mixing, comparable in size to the larger grains of sand. The largest of the purposely entrained bubbles are 1 mm (0.04 in.) in diameter; the smallest ones range down to 0.08 mm (0.003 in.) (entrained air bubbles are not visible to the naked eye, whereas entrapped air bubbles are). These purposely entrained air bubbles are uniformly distributed throughout the hardened cement paste, improve certain properties in both the fresh and hardened concrete, specifically giving it greatly improved ability to withstand damages from freezing and thawing (see Section 1.2.9).

If the hardened concrete is wet and then freezes, moisture in the concrete expands as it turns into ice. As the moisture expands, it is forced to move through the pores in the cement paste. If the moisture must move very far, pressures high enough to crack the concrete can develop. The entrained air bubbles, closely spaced and uniformly distributed throughout the hardened cement paste, act as empty chambers into which the expanding water can flow, thus relieving the otherwise disruptive pressure caused. It is important to note, however, that entrapped air (visible bubbles) does not offer any freezing-and-thawing damage resistance.

STUDY QUESTIONS

CCS-4 Chapter 2 Concrete Materials

1. Portland cements set and harden by the process called _____.
2. Most pozzolans reduce the _____ of concrete by filling in the spaces between _____ particles, and also improve its _____.
3. Concrete made without coarse aggregate is usually called _____ or _____.
4. Aggregate is referred to as fine aggregate when it is _____ mm (in.) or smaller.
5. Aggregate properties that affect concrete quality are _____.
6. Aggregate producers may sort aggregates by size, then recombine them in proportions to meet a grading specification. *True or False?*
7. In general, concrete mixtures using aggregates with a _____ particle size distribution curve will produce the best results.
8. Generally, any water that is _____ can be used for making concrete.
9. Seawater may cause _____ in reinforced concrete.
10. A concrete mixture may be designed using _____ to change freshly-mixed (plastic) and hardened properties.
11. Superplasticizers, pumping aids, and air entrainers are examples of _____.
12. A(n) _____ is defined as any material deliberately added to concrete before or during mixing, other than cement, water, aggregates, and fiber reinforcement.
13. Accelerating admixtures are useful when concreting in _____ temperatures.
14. _____ are added to accelerate the set of the shotcrete.
15. _____ are sometimes used in the concrete mixture when temperatures are high when placing concrete.
16. Water reducers are used to _____.
17. Air is intentionally entrained in concrete mainly to _____.

ANSWERS TO THE STUDY QUESTIONS ARE LOCATED IN APPENDIX A

SECTION 3

CCS-4 Chapter 3 Mixture Proportioning

- 3.1—Water-Cementitious Materials Ratio
- 3.2—Concrete Proportioning (Applied to Shotcrete)

CHAPTER 3—MIXTURE PROPORTIONING

This chapter explains the mixture proportioning process, also called mixture design. Concrete mixtures are usually proportioned (designed) by concrete suppliers or by laboratories that specialize in concrete testing and design.

The mixture designer selects the amount of cement, water, aggregates, and admixtures needed to produce a cubic meter (cubic yard) of concrete, based on a combination of experience, knowledge of the materials, and trial batches. The designer tries to meet four objectives:

1. The hardened concrete must have the strength, wear resistance, and durability called for by the job specifications;
2. The fresh concrete must be workable enough for the job;
3. The mixture must be economical; and
4. Shrinkage should be minimized.

3.1—Water-Cementitious Materials Ratio

For any particular set of materials and conditions of curing, the quality of hardened concrete is determined by the amount of water used in relation to the amount of cement. The following are some advantages of reducing the water content:

- Increased compressive strength;
- Lower permeability and lower absorption;
- Increased durability;
- Better bond to concrete and to reinforcing steel; and
- Reduced cracking due to shrinkage.

Some workers prefer to make the concrete mixture as wet as possible because this reduces the labor of placing (but not necessarily the overall labor requirements). This is not a good idea because adding water usually results in greater shrinkage and a lower strength that may not meet the specifications.

Engineers and specifiers use a term called water-cement ratio (w/c) to indicate how much water is in the mixture. It is simply a fraction or proportion arrived at by dividing the weight of water in a batch of concrete by the weight of cement. A cubic meter of concrete containing 200 kg of water and 400 kg of cement would have a w/c of

$$w/c = (200 \text{ kg water}) / (400 \text{ kg cement}) = 0.50$$

Or, a cubic yard of concrete containing 300 lb of water and 600 lb of cement would have a w/c of

$$w/c = (300 \text{ lb water}) / (600 \text{ lb cement}) = 0.50$$

With the growing use of pozzolans described in Section 2.2 (silica fume, fly ash, and slag), the w/c

may be presented as w/cm to indicate the amount of cement plus pozzolan or total amount of cementitious material (cm). Then the ratio is referred to as water-cementitious materials ratio.

The strength of a given concrete mixture is governed primarily by its w/c (or w/cm). A lower w/cm will increase the strength of concrete. For any given set of materials, there is a certain w/cm for each strength level that can be produced. This ratio can be estimated from tests of concretes made with a different w/cm . Increasing the amount of water without increasing the amount of cement generally results in lower strength.

In properly-made concrete, each aggregate particle is completely coated with paste. Also, all of the spaces between aggregate particles are filled with paste. Therefore, if the aggregates are of satisfactory quality, the quality of the concrete depends mostly on the quality of the paste. In turn, the quality of the paste depends on the w/cm . For concrete mixtures that are workable (can be placed with a reasonable amount of effort), those with a low w/cm are stronger (Fig. 3.1) and more durable than those with a high w/cm .

Most concretes have a w/cm between approximately 0.4 and 0.7. A w/cm lower than 0.4 is used in low-permeability concrete and in high-strength concrete. A w/cm higher than 0.6 may be used in concretes where strength, durability, and water tightness are not important.

Durability usually means resistance to damage (deterioration) caused by freezing and thawing, erosion, corrosion, and chemical attack. Air-entrained concrete is able to withstand freezing and thawing much better than non-air-entrained concrete. Air entrainment should be used for all concrete that

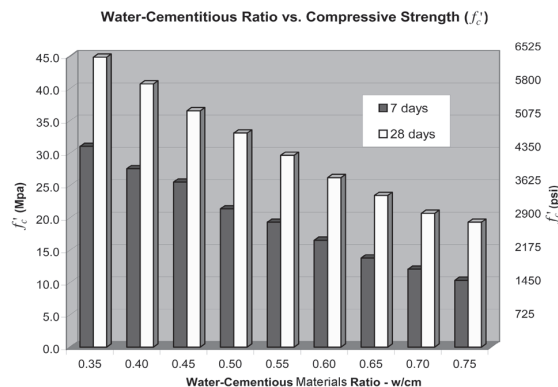


Fig. 3.1—Typical age-strength relationships for concrete. Note higher strengths with lower w/cm .

Table 3.1—Typical shotcrete mixture proportion, (ACI Guide to Shotcrete, Table 1.1, Gradation No. 2)

Materials	Quantity per m ³ (yd ³)
Cement, Type I	400 kg (650 lb)
Class C fly ash or silica fume	40 kg (70 lb)
Water	190 kg (315 lb)
$w/cm = 190 \text{ kg} / (400 \text{ kg} + 40 \text{ kg})$ $= 315 \text{ lb} / (650 \text{ lb} + 70 \text{ lb}) = 0.43$	
Fine aggregate (dry weight)	1250 to 1520 kg (2000 to 2500 lb)
Coarse aggregate (maximum size)	200 to 500 kg (350 to 850 lb)
Air-entraining agent	500 mL (18.5 fl. oz)

Table 3.2—Typical concrete (shotcrete) properties

Materials	Range of results, metric (Imperial)
Slump (wet-mix shotcrete)	50 to 75 mm (2 to 3 in.)
Unit weight (density)	2350 kg/m ³ (148 lb/ft ³)
Air content	4 to 7% (4 to 6.5%)
Compressive strength at 28 days	35 MPa (5000 psi)
Concrete temperature	13 to 25 °C (55 to 77 °F)

Table 3.3—Example of moisture content adjustment

Example	
Weight of dry sand as per mixture design	1250 kg (2000 lb)
Moisture content of sand at batch plant	5%
Weight of water in sand	$1250 \text{ kg} \times 5\% = 62.5 \text{ kg}$ $(2000 \text{ lb} \times 5\% = 100 \text{ lb})$
Weight of water in mixture as per mixture design	190 kg (315 lb)
Water to be added at batch plant	$190 \text{ kg} - 62.5 \text{ kg} = 127.5 \text{ kg}$ $(315 \text{ lb} - 100 \text{ lb} = 215 \text{ lb})$

might be exposed to freezing. Dusting and some types of thin surface scaling are caused by improper finishing and curing, and changing mixture proportions will not solve the problem.

3.2—Concrete Proportioning (Applied to Shotcrete)

The objective of concrete (shotcrete) mixture proportioning is to produce a concrete (shotcrete) that is economical, easy to place (workable), easy to convey (dry-mix shotcrete), easy to pump (wet-mix shotcrete), and easy to shoot. It needs to comply with the specifications of the project (slump for wet-mix, air content, strength, and durability). To reach this objective, the designer will introduce the largest possible volume of well-combined small and large aggregates and bind them together with good quality cement paste. As stated in Section 2.3, a properly-graded aggregate size distribution (Fig. 2.1(a)) is needed to improve shotcrete placement (increased compaction and build-up, less rebound, etc.).

A good quality of cement paste is governed by using a relatively low w/cm , as described in Section 3.1. In cases where the w/cm selected is too low to obtain adequate workability, special admixtures such as superplasticizers and/or water reducers can be used for proper placement. This approach keeps the w/cm low while producing high quality concrete (shotcrete).

After developing a mixture that will meet all of the specification requirements, the proportions of a proper shotcrete mixture can be described as shown in Table 3.1.

After appropriate testing, the mixture may produce properties presented in Table 3.2.

The amounts shown in the mixture design are not necessarily the same as the amounts used in batching the concrete. For example, the 190 kg (315 lb) of water shown includes moisture on the aggregates as well as added water. Sand is usually damp and the moisture on the sand particles becomes part of the mixture water.

Thus, it is easy to see that unless the aggregate moisture content is known accurately, the amount of water in the mixture is likely to be incorrect. With the wrong water content, the slump is likely to be incorrect.

This is why ready mixed concrete plants regularly measure their aggregate moisture content and adjust their mixture design accordingly to produce consistent concrete mixtures.

STUDY QUESTIONS

CCS-4 Chapter 3 Mixture Proportioning

1. The _____ of a given concrete mixture is governed primarily by its w/c ratio (or w/cm ratio).
2. Adding more than the specified amount of water to the concrete mix generally result in greater _____ and _____ strength.
3. The term w/cm refers to _____.
4. Concrete mixes with lower w/c ratios are _____ and more _____ than concretes with higher w/c ratios.
5. Most concretes have a w/cm ratio between approximately _____ and _____.
6. Is the following statement *true or false*?

The amount of cement plus pozzolan indicates the total amount of cementitious material (cm).

ANSWERS TO THE STUDY QUESTIONS ARE LOCATED IN APPENDIX A

SECTION 4

CCS-4 Chapter 4 What is Shotcrete?

4.1—Introduction

4.1.1—Dry-Mix Shotcrete

4.1.2—Wet-Mix Shotcrete

4.1.3—Comparison of Shotcrete Processes

CHAPTER 4—WHAT IS SHOTCRETE?

Shotcrete is concrete conveyed through a hose and pneumatically projected at high velocity onto a surface to achieve compaction, thus a method of placing concrete used primarily in the construction of vertical and overhead surfaces. Shotcrete allows construction of walls and other structures using only a one-sided form. In many situations, it is more economical than conventionally-cast concrete because of its versatility. Tanks, swimming pools, tunnels, mines, sculptured rocks, structural walls, erosion control embankments, retaining walls, and shear-walls are all structures commonly built using shotcrete. In addition, a wide variety of repairs also use shotcrete.

It is placed at various thicknesses against one-sided forms (or existing concrete or masonry structures and rock, earth, or other surfaces). Its build-up nature varies depending on various parameters, which will be described in Chapter 8, Shotcrete Placement. The shotcrete process creates rebound and overspray. Overspray is fine particles with just enough cement to stick to all nearby surfaces and rebound is defined as mainly large aggregate with some sand and cement that bounces or ricochets off the receiving surface and falls on to lower surfaces. The parameters that affects rebound are described in Chapter 8.

The nozzleman is the craftsman that physically directs the placement of the shotcrete. The nozzleman is responsible for the quality of the placed shotcrete and is an important member of a shotcrete crew. The nozzleman must have an understanding of the equipment's operation, safety procedures, and the material being placed.

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

4.1—Introduction

ACI defines shotcrete as “mortar or concrete pneumatically projected at high velocity onto a surface.” There are two shotcrete processes: dry-mix and wet-mix.

4.1.1—Dry-Mix Shotcrete

Dry-mix shotcrete is the process illustrated in Fig. 4.1 in which a dry mixture is conveyed pneumatically through a delivery hose at the end of which water is added at a nozzle.

More specifically, all ingredients, except water, are thoroughly mixed together. The cementitious-aggregate mixture is fed into a special mechanical feeder or gun called the delivery equipment. The material is

then carried by compressed air through the delivery hose to a nozzle body. The nozzle body is fitted inside with a water ring through which water is introduced under pressure and thoroughly mixed with the other ingredients. The material is shot from the nozzle at high velocity onto the receiving surface. Mixing occurs in the nozzle and as the material impacts the surface.

(The term gunite was once proprietary but became a generic term in 1967, according to the Gunite Contractors Association. Because the American Concrete Institute ceased using the term gunite for the dry-mix method, this manual will refer to it as dry-mix shotcrete.)

4.1.2—Wet-Mix Shotcrete

The wet-mix process is illustrated in Fig. 4.2 and has all the ingredients—including cement, chemical and mineral admixtures, aggregate, and mixing water—thoroughly mixed together before being pumped into a delivery hose or pipeline. Compressed air is added at the nozzle to increase the material velocity. The mortar or concrete is then shot from the nozzle at high velocity onto the receiving surface.

4.1.3—Comparison of Shotcrete Processes

Either process can produce shotcrete suitable for normal construction requirements. Different factors will determine the appropriate process for a particular application (experience of shotcrete crew, volume of shotcrete to be applied, job-site access, availability of materials, etc.).

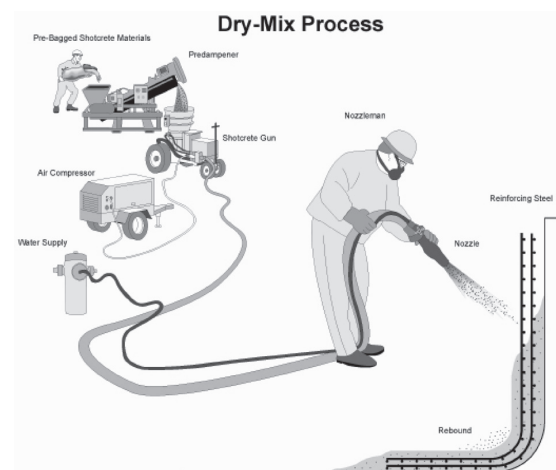


Fig. 4.1—Dry-mix shotcrete. Dry mixture conveyed pneumatically through delivery hose at end of which water is added at nozzle.

Table 4.1 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. It typically has a low w/cm and a high cementitious material content. Shotcrete acquires some of its unique properties from the placement process as the concrete is compacted when it strikes a surface. Therefore, it is important that shotcrete be projected at high velocity to achieve compaction. The nozzleman is responsible for ensuring that shotcrete is properly placed. The quality of shotcrete is largely dependent on the skill and knowledge of the nozzleman.

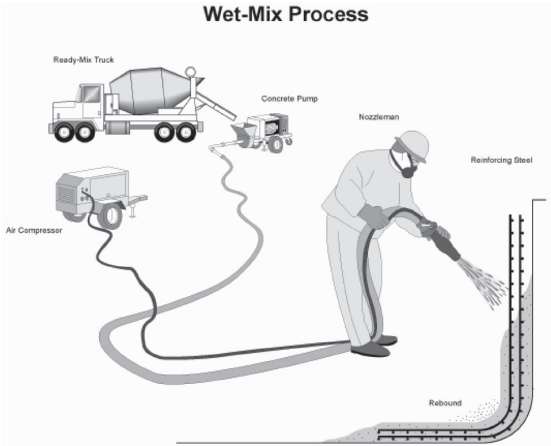


Fig. 4.2—Wet-mix shotcrete. Has all ingredients thoroughly mixed together before being pumped into delivery hose. Compressed air is added at nozzle.

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 nozzleman skill and experience, adapted delivery equipment, and properly proportioned shotcrete mixtures. As such, the following chapters provide additional pertinent information on Shotcrete Materials (Chapter 5), Shotcrete Equipment (Chapter 6), Preparation before Shooting, Shotcrete Placement Principles and Techniques, Communication, and Environmental Conditions and Precautions (Chapters 7 to 10). Chapters on Finishing and Tolerance Controls, Safety, and Testing/Quality are also presented (Chapters 11 to 13).

Table 4.1—Comparison of shotcrete processes

Dry-mix process	Wet-mix process
1. Instantaneous control over mixing water and consistency of mixture at nozzle to meet variable field conditions	1. Mixing water is controlled at mixing equipment and can be accurately measured
2. Better suited for placing mixtures for smaller concrete repair applications	2. Better assurance that mixing water is thoroughly mixed with other ingredients
3. Capable of being transported longer distances	3. Less dust and cementitious materials lost during shooting operation
4. Delivery hoses are lighter and easier to move	4. Normally has lower rebound, resulting in less waste
5. Lower volume per hose size	5. Higher volume per hose size

STUDY QUESTIONS

CCS-4 Chapter 4 What is Shotcrete?

1. What is overspray?
2. _____ is mainly large aggregate with some sand and cement that bounces or ricochets off the receiving surface and falls onto lower surfaces.
3. ACI defines Shotcrete as “mortar or concrete pneumatically projected at _____ onto a surface.”
4. When does mixing occur in dry-mix concrete?
5. Define Dry-mix shotcrete.
6. In the wet-mix shotcrete process, _____ is added at the nozzle to increase the _____.
7. Shotcrete typically has a low _____ ratio and a high _____ content.
8. _____ is a method of placing _____.

ANSWERS TO THE STUDY QUESTIONS ARE LOCATED IN APPENDIX A

