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Shotcrete—Guide

Reported by ACI Committee 506

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Shotcrete—Guide

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Shotcrete—Guide

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This guide is a companion document to ACI 506.2, “Specification for Shotcrete,” and provides information on materials and properties of both dry-mix and wet-mix shotcrete. Most facets of the shotcrete process are covered, including application procedures, equipment requirements, and responsibilities of the shotcrete crew. Other aspects, such as preconstruction trials, craftsman qualification tests, materials tests, finished shotcrete acceptance tests, and equipment, are also discussed.

Keywords: dry-mix shotcrete; mixture proportioning; placing; quality control; shotcrete; wet-mix shotcrete.

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PREFACE

This guide, based on many years of practice and experience, covers aspects of shotcrete construction, including materials, equipment, crew organization, preliminary preparation, proportioning, shotcrete placement, and quality assurance/quality control. Procedures vary from one region to another due to different materials, equipment, and techniques; therefore, adjustments for a particular project are often necessary.

New construction, repair, linings, coatings, refractories, underground support, and other special applications are also discussed. No attempt is made to provide guidelines for the

design of shotcrete installations. The purpose of this document is to serve as a guide to engineers and contractors and as commentary to ACI 506.2, “Specification for Shotcrete.”

Introduction

Shotcrete is an important and widely used construction technique. Because of continuing research and development in materials, equipment, and construction procedures, this guide is revised periodically to reflect current industry practice. Shotcrete is concrete placed by a high-velocity pneumatic projection from a nozzle. Shotcrete is thus a unique placement method for concrete. For the sake of readability, however, the word “shotcrete” is often used either to identify the shotcrete process (method of placement) or the shotcrete mixture.

Shotcrete has been used for structural concrete sections for decades. Although many engineers allowed shotcrete placement in their projects, there were no code provisions directly in ACI 318. In 2019, ACI 318 recognized the value of shotcrete in structural concrete for buildings and added shotcrete-specific code requirements.

History

In 1910, a double-chambered cement gun (dry-mix), based on a design developed by Carl Akeley, was introduced to the construction industry. The sand-cement product produced by this device was given the proprietary name “gunite”. In the ensuing years, trademarks such as Guncrete, Pneucrete, Blastcrete, Blocrete, Jetcrete, and the terms “pneumatically applied mortar or concrete” and “sprayed concrete” were introduced to describe similar processes. Between 1930 and 1950, gunite/shotcrete gained wide acceptance around the world because, at that time, gunite/shotcrete strength was superior to concrete and permitted the contractor to easily transport a sand cement mixture over long distances to difficult-to-reach areas. In the early 1930s, The American Railway Engineering Association introduced the term “shotcrete” to describe the gunite process. In 1951, the American Concrete Institute adopted the term “shotcrete” to describe the dry-mix process. It is now also applied to the wet-mix process and has gained widespread acceptance in the United States and around the world.

In the 1950s, wet-mix shotcrete, the use of coarse aggregate in both processes, the rotary gun for dry-mix shotcrete, and more efficient concrete pumps for wet-mix shotcrete were introduced. Many improvements were made to wet-mix equipment, primarily concrete pumps and materials, in the 1970s and 1980s. These improvements allowed pumping low-slump shotcrete mixtures longer distances at greater volumes. These innovations enhanced the utility, flexibility, and general effectiveness of the process. More recently, there have been advances and developments in admixtures and robotic placement of shotcrete, broadening the range of shotcrete applications.

Centrifugally applied concrete and low-pressure, low-velocity, wet-process mortar and concrete are not considered shotcrete and not covered in this guide because they do not comply with the current definition of shotcrete; they do not

achieve sufficient consolidation to be considered shotcrete (*“Application and Use of Shotcrete”* 1981).

Applications

Shotcrete can be used instead of conventional concrete in many instances, the choice being based on convenience and cost. Shotcrete offers advantages over conventional concrete in a variety of new construction and repair work.

Reinforcement details may complicate the use of shotcrete, but shotcrete is particularly cost effective where formwork is impractical or where forms can be reduced or eliminated; access to the work area is difficult; thin layers, variable thickness, or both, are required; or normal casting techniques cannot be employed. The excellent bond of shotcrete to many materials is sometimes an important design consideration.

New developments

The future of shotcrete is limited only by the speed of development of new materials, equipment, and techniques. A prime example of major expansion in the use of shotcrete is in early and final lining ground support in tunnels and mines. Improvements in prepackaged products; accelerating and setting-control admixtures; the use of fibers; and specially designed equipment, including robotic and remote-control shotcrete devices, have spurred the development of ground support techniques competitive with conventional steel rib and lagging supports (ACI 506.5R; ACI PRC-506.1).

Research and development

The ability of the shotcrete process to handle and place materials that have almost instantaneous hardening capabilities should result in expanding applications in the future. Areas of future research and development include shotcrete structural design, nozzle design, in-place testing techniques, materials, equipment mechanization, substrate evaluation, process automation, surface finish, and evaluation of reinforcement encasement. The use of shotcrete in the construction industry will increase as more aspects of the shotcrete method from design to installation are developed.

PART 1—GENERAL

1.1—Scope

1.1.1 Work specified (shotcreting processes)—The work should be classified as either structural or nonstructural. Shotcrete having a specified compressive strength of 4000 psi (28 MPa) or greater is considered structural shotcrete. Shotcreting can be applied by one of the two processes: wet-mix or dry-mix. Shotcrete is further described according to the size of aggregate used (coarse or fine). Refer to Table 1.1.1 for fine-aggregate grading (No. 1) and coarse-aggregate grading (No. 2).

Table 1.1.1—Grading limits for combined aggregates

Sieve size, U.S. standard square mesh	Percent by weight passing individual sieves	
	Grading No. 1	Grading No. 2
3/4 in. (19 mm)	—	—
1/2 in. (12 mm)	—	100
3/8 in. (10 mm)	100	90 to 100
No. 4 (4.75 mm)	95 to 100	70 to 85
No. 8 (2.4 mm)	80 to 98	50 to 70
No. 16 (1.2 mm)	50 to 85	35 to 55
No. 30 (600 μ m)	25 to 60	20 to 35
No. 50 (300 μ m)	10 to 30	8 to 20
No. 100 (150 μ m)	2 to 10	2 to 10

1.1.1.1 Dry-mix process—The dry-mix process consists of five steps and are as follows:

1. All dry ingredients, except water, are thoroughly mixed. Dry ingredients are predampened to contain approximately 6% moisture.
2. The cementitious aggregate mixture is fed into a special mechanical feeder or gun called the delivery equipment.
3. The mixture is usually introduced into the delivery hose by a metering device such as a feed wheel, rotor, or feed bowl. Some equipment uses air pressure alone (orifice feed) to deliver the material into the hoses.
4. The material is 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 mixes with the other ingredients.
5. The material is jetted from the nozzle at high velocity onto the surface to be shotcreted.

1.1.1.2 Wet-mix process—The wet-mix process consists of five steps and are as follows:

1. All ingredients, including mixing water, are thoroughly mixed.
2. The shotcrete mixture is introduced into the chamber of the delivery equipment.
3. The mixture is metered into the delivery hose and moved by positive displacement.
4. Compressed air is injected at the nozzle to increase velocity and improve the shooting pattern.
5. The concrete is jetted from the nozzle at high velocity onto the surface to be shotcreted.

1.1.1.3 Comparison of processes—Either process can produce shotcrete suitable for typical construction requirements. Differences in capital and maintenance cost of equipment, operational features, suitability of available aggregate, and placement characteristics, however, may make one or the other more attractive for a particular application. Table 1.1.1.3 gives differences in operational features and other properties that merit consideration.

Table 1.1.1.3—Comparison of dry-mix and wet-mix processes

Dry-mix process	Wet-mix process
Instantaneous control over mixture water and consistency of the mixture at the nozzle to meet variable field conditions	Mixture water is controlled at the mixing equipment and can be accurately measured
Better suited for placing mixtures containing lightweight aggregates or refractory materials	Better assurance that the mixture water is thoroughly mixed with other ingredients
Delivery hoses are easier to handle	Less dust and cementitious materials lost during the shooting operation
Well suited to conditions where the timing of placing the shotcrete cannot be predicted or is intermittent	Normally has less rebound, resulting in less waste
Lower volume per hose size	Higher volume per hose size

1.1.1.4 Coarse aggregate shotcrete—Although in its early years shotcreting was performed with fine-aggregate-based materials (mortar), most of today's applications (both wet-mix and dry-mix) include larger coarse aggregate (refer to Table 1.1.1 Grading No. 2).

There are six reasons for adding coarse aggregate to shotcrete:

1. Less cementitious materials required: The reduced surface area of coarse aggregate versus fine aggregate permits reducing cementitious content.
2. Reduced shrinkage: Coarse aggregate reduces drying shrinkage by reducing water and cementitious content.
3. Pumpability: The addition of coarse aggregate may improve pumpability for wet-mix.
4. In-place-density: The addition of coarse aggregate into plastic shotcrete improves the in-place density.
5. Improved economy: Reduction of cementitious content improves economy.
6. Sustainability: Reduction of cementitious content contributes to sustainability.

For both the dry-mix and wet-mix processes, however, coarse-aggregate shotcrete with more than 30% coarse aggregate as a percentage of total aggregate has greater rebound, is more difficult to finish, and cannot be used for thin layers. Coarse aggregate shotcrete requires the use of larger-diameter hoses and may create craters in the plastic shotcrete.

1.1.1.5 Types of shotcrete

1.1.1.5.1 Conventional shotcrete—Conventional shotcrete (shotcrete without special admixtures) is the most commonly used application for shotcrete and includes the following:

(a) *New structures*—Roofs, thin shells, walls, prestressed tanks, buildings, reservoirs, canals, swimming pools, boats, sewers, foundation shoring, ductwork, shafts, and artificial rock

(b) *Linings and coatings*—Over brick, masonry, earth, and rock; underground support, tunnels, slope protection, erosion control, fireproofing of steel, steel pipeline, stacks, hoppers, bunkers, steel, wood, and concrete; pipe protection; and structural steel encasement

(c) *Repair*—For deteriorated concrete in bridges, culverts, sewers, dams, reservoir linings, grain elevators, tunnels, shafts, waterfront structures, buildings, tanks, piers, seawalls, brick, masonry, and steel structures

(d) *Strengthening and reinforcing*—To strengthen and reinforce concrete beams, columns, slabs, concrete and masonry walls, steel stacks, tanks, and pipes; used for seismic rehabilitation of shear walls, boundary elements,

beams, columns, overhead joists, and slabs, and for strengthening of existing masonry and concrete walls; and used in structural interiors and exteriors because of its speed and flexibility of application

(e) *Ground support*—Extensively used as temporary and permanent ground support. It has become the primary method of ground support in mining and tunneling (ACI 506.5R). Shotcrete is also used extensively as lagging instead of wood for soldier pile and lagging shoring systems, and as the lagging in soil nailing (Society of Mining Engineers 2011). Soil nailing using shotcrete is a method of shoring that is used for both temporary and permanent ground support of soil retention systems

1.1.1.5.2 Refractory shotcrete—Shotcrete applications using high-temperature binders and refractory aggregates in refractory construction began in the mid-1920s, where it was used primarily for repair and maintenance of furnace linings. The refractory industry favors shotcrete because of the speed of installation and general effectiveness of the process. Shotcrete has become a major method of installation for all types of linings from several inches to several feet thick and is used in new construction and for repair and maintenance in steel and nonferrous metal; chemical, mineral, and ceramic processing plants; steam power plants; and incinerators.

Refractory shotcrete provides a viable alternate to traditional methods of refractory construction. Hot gunning procedures for high-temperature installations and bench shooting for thick layers have opened new fields for refractory shotcrete use.

1.1.1.5.3 Special shotcrete—Special shotcrete includes proprietary mixtures for corrosion- and chemical-resistant protection. Portland cement with admixtures or other types of cements are used to produce special corrosion- and chemical-resistant properties. Special cements include magnesium phosphate cement and calcium aluminate cement. Special shotcrete applications are used for caustic and acid storage basins, chimneys and stacks, process vessels, chemical spillage areas, sumps, trenches, pollution control systems, and concrete repair in other highly aggressive environments. The application of polymer (latex) shotcrete is not recommended due to numerous failures and is not covered in this document.

1.1.1.5.4 Fiber-reinforced shotcrete—The addition of steel or synthetic fibers in conventional and refractory shotcrete has been gaining favor during the past four decades. Fibers at normal addition rates (typically between 0.1 and 1.0% volume fraction) can provide improved flexural and

shear capacity, fracture toughness, and impact resistance. For refractory shotcrete, stainless steel fibers increase resistance to thermal shock, temperature cycling damage, and crack development. The addition of polyolefin fibers and other low-melting-point fibers improve the fire resistance of shotcrete due to the fibers creating steam relief vents when exposed to fire (Tatnall 2002).

Some specific applications where fiber-reinforced shotcrete (FRS) can be cost effective are slope protection; ground support in tunnels and mines; concrete repair; swimming pools; thin shell configurations; and refractory applications such as boilers, furnaces, coke ovens, and petrochemical linings (Sections 2.1.7.4, 2.3, and 2.4.8).

1.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

air lance—typically a pipe through which high-pressure air is delivered; also called “blowpipe”.

collated fiber—fibers bundled together either by cross-linking or by chemical or mechanical means.

cuttings—shotcrete material that has been applied beyond the finish face and is cut off in the trimming or rodding process.

delivery equipment—equipment that introduces shotcrete material into the delivery hose.

finisher—craftsman that trims and finishes the surface of the shotcrete.

impact velocity—velocity of the material particles just before impact.

mockup—full-size structural or architectural model built to scale for evaluation.

nozzle body—device at the end of the delivery hose that has a regulating valve and contains a manifold (water or air ring) to introduce water or air to the shotcrete mixture; a nozzle tip is attached to the exit end of the nozzle body.

nozzleman—craftsman on shotcrete crew who manipulates the nozzle, controls consistency with the dry process, and controls final deposition of the material.

overspray—shotcrete material deposited away from intended receiving surface.

pneumatic feed—shotcrete delivery equipment in which material is conveyed by a pressurized air stream.

positive displacement—wet-mix shotcrete delivery equipment in which a pump or other nonpneumatic means pumps the material through the delivery hose in a solid mass.

predampening—in the dry-mix process, the controlled addition of water to the aggregates or premixed shotcrete materials during batching to adjust the moisture content of the shotcrete mixture before introduction into the gun.

prehydrating—in the dry-mix process, adding water to shotcrete materials in the delivery hose at some distance before the nozzle.

pump operator—craftsman on wet-mix shotcreting crew who operates delivery equipment.

rodman—craftsman on the shotcrete crew who trims and finishes shotcrete using a rod or other tools; needed on larger jobs to assist the finisher.

rolling—result of applying shotcrete at angles less than 90 degrees to the receiving surface, resulting in an uneven, wavy, textured surface at the outer edge of spray pattern.

sand lens—sand pocket shaped as a lens.

sand pocket—zone in the shotcrete containing fine aggregate with little or no cement.

shadow—area behind an obstacle that is not impacted and compacted by the shotcrete stream; in hardened shotcrete, refers to any porous area behind an obstacle such as reinforcement.

wetting—in the dry-mix process, the addition of mixing water to shotcrete materials just before the material exits the nozzle.

1.3—References: Refer to Part 7

1.4—Submittals

1.4.1 Data on the source of all materials to be used should be submitted to the design authority for approval. To achieve approval, materials should either be certified by the supplier that it meets specified requirements or tested on a regular basis to confirm compliance. The project size and character will dictate which procedure is suitable. Mixture proportions should be submitted to satisfy specified project requirements. A design or proof mixture should be prepared and tested or a previously qualified mixture may be submitted. The results of all required tests, and qualifications of the nozzlemen, should be submitted to the design authority. In addition to qualifying the nozzleman, the shotcrete contractor should also provide evidence of qualification and previous experience for the type of shotcrete specified. If required, submit the name of proposed testing agency.

1.4.1.1 *Mixture proportions*—Refer to 2.5.

1.4.1.2 *Compressive strength*—Refer to 2.4.2 and 2.5.

1.4.1.3 *Water-cementitious materials ratio (w/cm)*—Refer to 2.5.3.

1.4.1.4 *Admixtures*—Refer to 2.1.5 and 2.5.

1.4.1.5 *Cementitious materials*—Refer to 2.1.1.

1.4.1.6 *Aggregate*—Refer to 2.1.3.

1.4.1.7 *Aggregate absorption*—Refer to 2.1.3.2.

1.4.1.8 *Craftsman qualifications*—Refer to 1.6 and 5.3.

1.4.1.9 *Contractor qualifications*—Refer to 1.6.

1.4.1.10 *Water*—Refer to 2.1.4.

1.4.1.11 *Fiber-reinforced shotcrete*—Refer to 2.1.7.4, 2.3, and 2.4.8.

1.4.1.12 *Boiled absorption test results*—Refer to 2.4.7.

1.4.1.13 *Hydration control admixtures*—Refer to 2.1.5.5 and 2.1.5.5.2.

1.4.1.14 *Repair procedures*—Refer to 3.9.

1.4.1.15 *Curing procedures*—Refer to 2.1.8 and 3.6.

1.4.1.16 *Testing agency*—Refer to 1.6.2 and 1.6.4.

1.5—Preconstruction testing by contractor

Preconstruction testing should be conducted on large, complex jobs if previous data are not available, if proper

ties other than strength affect the design criteria, or if design requirements vary from one portion of the work to another.

Before shotcrete construction starts, it is advised to conduct preconstruction testing. On relatively small jobs and where the materials, mixture proportions, equipment, finish, and personnel have given satisfactory results on previous work, preconstruction testing may not be warranted.

The purpose of preconstruction testing is to ensure the shotcrete work will achieve the following objectives:

- (a) The shotcrete placement can properly encase the reinforcement given the reinforcement design (size, spacing, and amount)
- (b) The material meets the project specifications
- (c) The finish will meet the owner's expectations

1.5.1 Reinforcement—To determine if the reinforcement can be properly encased, shooting mockup panels that simulate actual job conditions, such as reinforcing bar congestion,



Fig. 1.5.1a—Typical example of mockup for evaluation of reinforcement encasement.



Fig. 1.5.1b—Crew shooting mockup panel.

tion, provides a sufficiently reliable indication of the quality to be expected in the structure. The mockup panel should always be constructed with reinforcement similar to the most heavily reinforced section to be shot. The cut surfaces of the specimens should be carefully examined. Saw or break the panel when necessary to check the soundness and uniformity of the material. All cut and broken surfaces should be dense and mostly free from laminations, voids, and sand pockets. For evaluation of shotcrete, refer to **ACI 506.4R** and Fig. 1.5.1a and 1.5.1b.

1.5.2 Material—Shoot material test panels for evaluation of material properties (1.6.3). A separate panel should be fabricated for each mixture proportion being considered and for each shooting position to be encountered in the structure such as horizontal, vertical, or overhead. Test panel conditions should simulate field conditions as accurately as possible. For dry-mix shotcrete with accelerator, setting time should be tested in accordance with **ASTM C403/C403M** and the early-age compressive strength should be determined using the modified beam testing method or penetration resistance method. After the material attains 1400 psi (10 MPa), cores may be taken to conduct laboratory testing, including compressive strength at 7 and 28 days. Cores for compression testing should not contain reinforcement. Mockup panels may be cored for evaluation on the day following placement. Slump and air content for wet mix may be tested prior to shooting either a material or mockup test panel. Air content of the in-place material is not typically tested.

1.5.3 Finish—The contractor may shoot and finish several sample panels to demonstrate finishes for acceptance.

1.6—Testing during construction: quality assurance and quality control

Shotcrete is a unique method of placing concrete and is suited to unusual applications that require careful attention to details from design through construction. Therefore, it is essential to establish quality assurance/quality control (QA/QC) procedures to ensure that the final product functions as designed and has a satisfactory life expectancy. Among the factors that determine the quality of the shotcrete are design, materials, application equipment, craftsmanship, and installation techniques.

Implementing a QA/QC program for a shotcrete installation requires a holistic approach. The size and character of the project usually determines the amount of effort that should be expended on QA/QC. The QA/QC costs should be balanced with the benefits to be derived. Appendix A in **ACI 506.4R** provides guidance for QA/QC for shotcrete projects. QA/QC includes testing procedures and constant monitoring of every phase of the shotcrete installation. The owner/engineer should have an understanding of and experience in the application of shotcrete and have sufficient flexibility to adapt the specifications to specific field conditions. **ACI 121R** and **ACI 311.4R** contain valuable guidance on the establishment of QA/QC programs.

A successful project is dependent on not only an experienced nozzleman, but an experienced contractor and shotcrete crew. Only competent, experienced, and trained

craftsmen working together and provided with proper equipment and materials will produce high-quality shotcrete. Job specifications for structural shotcrete should require that the nozzlemen have attained relevant ACI nozzleman certification. Although a nozzleman is ACI certified, the nozzleman may not have sufficient experience to shoot heavily reinforced sections or complex structures, which is why preconstruction testing should be considered. The contractor and nozzleman should have a traceable history of completed, acceptable shotcrete work similar to that required for the project. The contractor's principals and shotcrete crew should have a successful background in shotcrete, as determined by reference and reputation. Supporting technical or testing data should supplement any literature or information submitted by the contractor.

Placement technique is critical to obtain high-quality shotcrete. Good materials placed poorly will produce an unsatisfactory product. The procedures and techniques described in **Part 3** of this guide should be followed closely because they represent good shotcrete practice.

Proper design is another important factor in a successful shotcrete application. Shotcrete design may be empirical or based on analytical procedures for concrete design. These procedures are used to determine shape, thickness, reinforcement, and mixture proportions. Quality control ensures that these items are constructed as designed; it will not ensure that the application will function as designed. This guide does not provide guidance for the design of shotcrete structures.

1.6.1 Quality assurance—Activities typically conducted by the owner's representative should include conducting construction monitoring, QA testing, and approval of the QC testing procedures. QA testing is commonly provided at a frequency of approximately 10% of QC testing. QA is not required for every shotcrete project but may be important for large-scale projects such as bridge repair and lining of tunnels. Typical QA work includes:

- (a) Visual inspection for cracks, discoloration, and leaks
- (b) Sounding with a hammer; on specific projects or if problems are suspected, specific tests may be performed
- (c) Evaluating volume of water or grout injected into a section, exploratory chipping for delaminations, coring, bond pull-off testing, and nondestructive testing

A knowledgeable and qualified inspector is a necessary requirement for implementing QA. The inspector should be familiar with plans, specifications, and applicable standards. The inspector should understand all facets of the shotcrete process, especially the installation techniques described in Part 3. The inspector should continuously inspect the work, paying attention to materials, forms, reinforcement, equipment, placement, finishing, curing, and protection of the finished product. If defects are detected, the inspector should recommend immediate corrective action, including removal of loose shotcrete, or documentation of deficiencies for later repairs. The inspector typically monitors field testing. Refer to **ACI 506.4R** for recommended tests and inspection. The testing agency laboratory should be certified in accordance with **ASTM C1077**.

The inspector should document any nonconformance of shotcrete placement and notify both the contractor and engineer as soon as the nonconformance is identified. The contractor should implement corrective action. A follow-up inspection should be conducted to confirm that the corrective action properly resolves the nonconformance.

1.6.2 Testing shotcrete: quality control—QC normally includes mixture design review, shotcrete construction monitoring, and providing shotcrete samples. The default test for a typical shotcrete project is for the contractor to prepare shotcrete samples by shooting sample material panels (1.5.3), which are cored and tested for compressive strength. In addition, flexural strength tests may be required. When placing wet-mix shotcrete, the air content and temperature of the mixture (delivered material) should also be documented by the testing agency prior to placement when sample material panels are shot.

The QC program should include the following:

(a) *Shotcrete execution plan*—The shotcrete contractor should prepare this plan. This should include shotcrete construction procedures and checklists (work method plan including shotcrete batching, mixing, supply, and placing procedures). The QC checklist should list critical features to be checked prior to placement, during placement, and after placement. A checklist should address surface preparation, reinforcement (size, location, and clearance), forms, access, equipment, personnel, mixture, finishing, curing, and consider precautions needed due to anticipated weather conditions.

(b) *Inspection and testing plan*—The specifier and materials testing agency, in conjunction with the shotcrete contractor, should prepare this plan. The content of the inspection and testing plan should include items to be inspected or tested, method, time and frequency of inspection and testing, and acceptance and rejection criteria. If required, the plastic characteristics of the shotcrete mixture, such as air content, temperature, and setting time, should be documented. Test the plastic characteristics of the shotcrete mixture from the concrete chute for wet mix. Slump and air content are not typically measured for dry mix.

(c) *Construction monitoring or daily report*—A daily record of placement should be submitted to the inspector and sent to the owner, engineer, supplier, and contractor as part of the project record. The daily report should include project details, such as nozzleman information, amount of material placed, documentation of samples prepared, and any field test results.

1.6.2.1 Test samples—Refer to 1.6.3.

1.6.2.2 Compressive strength—Refer to 2.4.2.

1.6.2.3 Flexural strength—Refer to 2.3, 2.4.3, and 2.4.8.

1.6.2.4 Air content—Refer to 2.4.4.

1.6.2.5 Material temperature—Refer to 3.4.4, 3.4.5, and 3.4.6.

1.6.3 Test panels—There are three different types of field test panels that are shot, not cast, and each has a different objective:

(a) Material panels are shot for determining material properties

(b) Qualification panels or a mockup are used in preconstruction testing

(c) Nozzleman evaluation panels are used to evaluate nozzlemen

1.6.3.1 Material test panels—Test panels provide a form for placing shotcrete that will be tested to determine the quality of the placed shotcrete and compliance with specified shotcrete strength requirements. Material test panels are typically oriented in the vertical position and placed against another structure that is rigid enough to prevent movement or deflection of the test panel. In special circumstances, test panels are oriented in the overhead position; however, great care should be taken, as material can fall out of the unreinforced panels and cause injury. An overhead panel is not generally necessary for demonstrating compliance with specified strength requirements.

ACI 506.2 specifies the minimum dimension of a test panel to be 16 x 16 in. (400 x 400 mm) in dimension with a minimum depth of 5 in. (125 mm). Care should be taken to ensure that the thickness of shotcrete placed will allow trimmings of each end of each recovered core to provide the minimum required test specimen length. **ASTM C1140/C1140M** specifies that the minimum core diameter for compression testing should be no less than nominal 3 in. (75 mm). Cores less than nominal 3 in. (75 mm) in diameter are not recommended because smaller cores are more sensitive to minor flaws that can produce varied and erroneous test results. Special care should also be taken when extracting, curing, and handling small-diameter cores for the same reason.

The 16 x 16 in. (400 x 400 mm) test panel specified by ACI 506.2 has the additional advantages of being lighter (110 lb [50 kg] versus 175 lb [80 kg] ASTM panel) and yet thick enough (5 in. [125 mm]) to allow coring a 3 in. (75 mm) diameter core bit, which typically provides a 2.8 in. (71 mm) actual diameter core (3.25 in. [82.5 mm] core bits are available). The 2.8 in. (71 mm) diameter by 5 in. (125 mm) long core approaches the 2:1 target length-to-diameter ratio goal for a compressive test sample. The larger 24 x 24 in. (600 x 600 mm) ASTM panel allows for the extraction of more cores if needed. Both panels have formed sides that may interrupt the air flow and contribute to the formation of sand lenses and voids near the form walls. Therefore, ASTM C1140/C1140M does not permit taking cores closer than the panel thickness plus 1 in. (25 mm) from the edge of the panel that limits the area from which cores can be extracted.

Normal testing ages for compressive strength are 7 and 28 days; however, shorter periods may be required for specific applications or conditions such as tunnel shotcrete requiring high early strength. Sampling is usually done once a day or every 50 yd³ (40 m³), whichever is greater. Sampling and testing, however, should be varied according to the size, complexity, issues encountered, and objectives of the project. Sampling should be done in accordance with

ASTM C1385/C1385M. Depending on conditions, such as strength requirements, environmental conditions, or as a backup to the owner's testing, shooting extra panels or taking cylinders of the mixture (wet-mix only) is advised.

Because handling of large heavy panels is difficult, cores should be taken when sufficient strength has been achieved from the panels at the jobsite so just the cores are transferred to the test laboratory. Sampling procedures (panel size and shape) should be specified in the contract documents. As with all material samples, proper curing and handling of the panels and cores is required to ensure a proper evaluation of the shotcrete.

In some situations, with familiar materials, molded cylinders can be made of the wet-mix shotcrete mixture prior to shooting. Testing of the shotcrete mixture using molded cylinders, however, does not indicate the strength of the in-place shotcrete. Like cast-in-place concrete, sample cylinders only provide an indication of the as-delivered shotcrete mixture's strength capability. The placement of concrete (shotcrete mixture) via the shotcrete process achieves consolidation through impact velocity. Molded cylinders of the shotcrete mixture will have higher air content and, therefore, lower compressive strength than in-place shotcrete. Additionally, as proved by testing, compaction that occurs during shotcrete placement improves the characteristics of the concrete (shotcrete mixture).

Typically, shotcrete compression test results exceed most specified strengths for conventional shotcrete applications for two reasons:

1. Extra cementitious material in the shotcrete mixture: Shotcrete mixtures pumped through a small-diameter line require extra cementitious material to coat smaller aggregate and serve as a line lubricant.
2. Low *w/cm* required: A low *w/cm* is needed so that the shotcrete will adhere to a vertical surface or not slump when stacked.

1.6.3.2 Nozzleman/project qualification panels (mockup)—The purpose of nozzleman/project qualification panels is to qualify the nozzleman crew and materials for a particular project with specific materials, reinforcement, and site constraints. Panels are typically mockups of the project with the most complex reinforcement layout required of the project (Sections 1.5 and 5.3.3).

1.6.3.3 Nozzleman certification panels—The purpose of the evaluation panel is to determine if the nozzleman has the basic skills to properly place shotcrete and achieve sufficient encasement of reinforcement. Typically, evaluation panels are 30 x 30 x 3 in. (750 x 750 x 75 mm) with sample reinforcement. Evaluation panels are made by and under the supervision of and evaluated by an ACI-certified shotcrete nozzleman examiner and should only be used to evaluate a nozzleman's skill (Fig. 1.6.3.3). Guidance for the visual evaluation of core quality is given in **ACI 506.6T**.



Fig. 1.6.3.3—Shooting certification panel with reinforcement.

1.6.4 Testing in-place shotcrete—An aspect of QA/QC is the physical testing of the shotcrete before and after placement. The agency providing the testing, inspection, or both, should meet the requirements of [ASTM E329](#) and the laboratory certified in accordance with [ASTM C1077](#).

Other testing that may be conducted includes water absorption, volume of permeable voids, drying shrinkage, and resistance to freezing-and-thawing cycles. FRS may also be tested for flexural capacity ([Section 2.4.8](#)). If boiled absorption in accordance with [ASTM C642](#) is required, a baseline boiled absorption value of the shotcrete mixture should be established. The acceptable value of the shotcrete boiled absorption should be compared to the shotcrete mixture value ([Section 1.7.6.3](#)).

1.6.5 Testing shotcrete for bond to substrate—The shotcrete process of driving cementitious paste at high velocity onto a substrate typically achieves good bond. If required, bond tests may be performed in accordance with [ASTM C1583/C1583M](#) ([Section 2.4.9](#)).

1.6.6 Reporting of quality assurance test results—Report results of all tests to contractor, material supplier, owner, and the design authority.

1.7—Acceptance

1.7.1 Shotcrete that exhibits laminations and voids, exceeding the specified limits, should be removed, replaced, or repaired. [ACI 506.4R](#) provides guidance for engineers, inspectors, contractors, and others involved in accepting, rejecting, or evaluating in-place dry-mix or wet-mix shotcrete ([Section 1.6.1](#)).

1.7.2 Shotcrete should meet project specifications for line grade, finish, and tolerances ([Sections 3.3](#) and [3.8](#)).

1.7.3 Shotcrete that has previously failed to meet one or more requirements may be repaired to bring the shotcrete into compliance ([Section 3.9](#)).

1.7.4 Shotcrete that fails to meet specified requirements may be accepted or rejected by the design authority. The

contractor should make modifications to the mixture or procedures to ensure the balance of the work meets specifications ([Section 2.5](#)).

1.7.5 Acceptance of shotcrete strength is typically based on compressive strength results obtained from drilled cores ([ASTM C1604/C1604M](#)) taken from a shotcrete panel ([Section 1.6.3](#)). If other characteristics are to be evaluated, the use of data from nondestructive testing (NDT) devices such as impact hammers or probes ([ASTM C805/C805M](#); [ASTM C803/C803M](#)), ultrasonic equipment ([ASTM C597](#)), and pull-off devices ([ASTM C1583/C1583M](#)) may be useful in determining the uniformity and quality of the in-place shotcrete. These tests, however, may not provide reliable values for compressive strength unless a correlation has been established between the NDT data and destructive test data for a particular shotcrete mixture. Refer to [ACI 228.2R](#) for additional information on NDT. If cores are to be taken for evaluation for acceptance, criteria should be established by the architect/engineer ([ACI 506.4R](#)).

1.7.6 Compliance with test properties—All tests should be performed by an agency meeting the requirements of [ASTM E329](#) ([Section 1.5](#)).

1.7.6.1 Compressive strength—The compressive strength of shotcrete is adequate if the average of the three cores from a test panel or from in-place shotcrete exceeds 85% of the specified compressive strength and no single core is less than 75% of the specified compressive strength ([ACI 506.2](#)). This reduction factor is used to compensate for the effects that coring has on the extracted specimens ([ACI PRC-214.4-21](#) Chapter 3).

1.7.6.2 Flexural strength and toughness of fiber-reinforced shotcrete—Refer to [ACI PRC-506.1](#) and [Section 2.4.8](#).

1.7.6.3 Boiled water adsorption test results, if specified, should be in accordance with [ASTM C642](#) but can vary widely depending on mixture and aggregate, so preconstruction testing should be conducted ([Section 2.4.7](#)).

1.7.6.4 FRS may require [ASTM C1550](#) or flexural toughness testing according to [ASTM C1609/C1609M](#) ([Section 2.4.8](#); [ACI PRC-506.1](#)).

1.7.6.5 Bond strength is the average of three cores ([Section 2.4.9](#)).

PART 2—PRODUCTS

2.1—Materials

Materials that produce high-quality mortar or concrete should also produce high-quality shotcrete. All materials should meet the requirements of [ASTM C1436](#). Shotcrete that is required to have special properties such as low density, insulating qualities, quick setting, or resistance to heat or acids may dictate the use of special aggregates, cements, or admixtures.

2.1.1 Cement

2.1.1.1 Portland cement—Most shotcrete is produced with Type I or II cement conforming to [ASTM C150/C150M](#). Other cementitious materials, such as blended hydraulic cements, should meet [ASTM C1157/C1157M](#).

2.1.1.2 Alternate cements—Other types of cements have been used successfully in shotcrete refractory applications and in other cases where rapid hardening, heat resistance, and early strength gain is required. They are also used in situations where resistance to certain acids, sulfate resistance, low permeability, or low shrinkage is required. For refractory linings, calcium-aluminate cement is commonly used in combination with a heat-resistant aggregate.

2.1.2 Supplementary cementitious materials—Most shotcrete mixtures contain supplementary cementitious materials (SCMs) that make up a portion of the cementitious component. Some materials, such as pozzolans, do not have any cementitious properties but contain silica in a reactive form that, when used with portland cement, reacts to form cementitious compounds. Other materials, such as slag cement, do exhibit cementitious properties.

For use in shotcrete, supplementary cementitious materials, sometimes referred to as mineral admixtures, must meet requirements of **ASTM C1697**. They may be used individually or in combination. They may be added to the shotcrete mixture as blended cement, as a separately batched ingredient, or as a replacement to the cementitious material. The addition of SCMs may improve the consistency and workability of fresh concrete. Adding SCMs increases the total fines content and may reduce bleeding. Shotcrete mixtures with SCMs can be proportioned to meet strength requirements of all cement mixtures. Depending on the selected type and amount of SCMs, the initial strength may be lower with cementitious material but the strength gain can continue for a longer period when compared to an all-cement mixture and likely achieve higher long-term ultimate strengths. Shotcrete with SCMs generally requires more attention to curing. Mixtures with SCMs may provide more resistance to sulfate attack and to alkali-silica reactivity if reactive aggregates exist.

2.1.2.1 Fly ash—Fly ash is a by-product of coal-fired furnaces at power generation facilities. Fly ash used in concrete should conform to **ASTM C618**. Typically, the amount of fly ash used in a mixture is approximately 10 to 25% but can vary from 5 to 65% by mass of the cementitious material. Characteristics of fly ash vary significantly depending on the source of the coal being burnt. Class F fly ash is normally produced by burning anthracite or bituminous coal and has a low calcium content. Class C fly ash is normally produced when sub-bituminous coal is burned and has cementitious and pozzolanic properties. Fly ash is also an aid to pumping of wet-mix through small-diameter lines because the fly-ash particles are spherical in shape, which improves flow characteristics.

2.1.2.2 Slag cement—Slag cement is a nonmetallic manufactured by-product from a blast furnace when iron ore is reduced to pig iron. The liquid slag is rapidly cooled to form granules, which are then ground to fineness similar to portland cement. The slag cement should meet the requirements of **ASTM C989/C989M**. Slag cement is typically used at 20 to 70% by mass of the cementitious materials. There are three grades of slag cement. Generally, higher-grade slag cement will be finer and have greater strength development.

2.1.2.3 Silica fume—Silica fume is a highly reactive pozzolanic material and is a by-product (flue gas) from the manufacture of silicon or ferrosilicon metal. Silica fume is an extremely fine powder, with particles 100 times smaller than the average cement grain. Silica fume should meet **ASTM C1240** requirements. It is generally added at 5 to 12% by mass of cementitious materials. Because of its fineness, silica fume fills in voids between the cement particles, which reduces the permeability and increases the strength of shotcrete. However, due to its fine particle size resulting in increased surface area, silica fume increases the water demand. Silica fume comes in three forms: slurry, undensified, and densified. All three forms are acceptable for use in shotcrete. When using slurry, the water portion of the slurry should be compensated for in the water-cementitious materials ratio (w/cm); that is, the water in the slurry counts as mixing water for both dry-mix and wet-mix shotcrete. Undensified silica fume is mainly used in premixed dry-bag shotcrete products. Densified silica fume is best used in wet-mix shotcrete (**Morgan 1988**).

2.1.2.4 Raw or calcined natural pozzolans—Natural pozzolans are materials covered by ASTM C618. Typical pozzolans are metakaolin. These materials are manufactured by firing of natural materials.

2.1.3 Aggregate

2.1.3.1 Normalweight aggregate—Normalweight aggregate for shotcrete should comply with the requirements of **ASTM C33/C33M**. The combined aggregate should meet one of the gradations shown in Table 1.1.1. Grading No. 1 should be used for fine-aggregate shotcrete and Grading No. 2 for coarse aggregate shotcrete.

Aggregates failing to comply with the gradations shown in Table 1.1.1 may be used if preconstruction testing proves satisfactory results or if acceptable service records of previous use are available. Aggregate gradation also affects the ability of the shotcrete mixture to transport fibers. Mixture design—particularly aggregate content and proportions—may require modifications in such cases.

2.1.3.2 Lightweight aggregates—Lightweight aggregates should conform to **ASTM C330/C330M** if used in shotcrete. The aggregate should meet one of the gradations shown in Table 1.1.1. Wet-mix shotcrete with lightweight aggregate is seldom used and is difficult to pump because the aggregate absorbs water, which reduces the consistency of the mixture. Presaturating the lightweight aggregate before batching improves pumpability. Lightweight aggregate mixtures have been shot for wall and floor construction. Shotcrete is frequently employed for fireproofing structural steel members using lightweight aggregates in the mixture.

2.1.4 Water

2.1.4.1 Mixing water—Potable water is preferred mixing water in concrete without testing. Other water should meet the requirements of **ASTM C1602/C1602M** and be clean and free from substances that may be injurious to concrete or steel. If water meeting ASTM C1602/C1602M is not available, the water should be tested to ensure that compressive strengths of mortar cubes made with it is at least 20% of mortar cubes made with distilled water.

2.1.4.2 Curing water—Curing water should be free from substances that may be injurious to concrete. Water for curing architectural shotcrete should be free from elements that cause staining. The temperature of the curing water should not be more than 20°F (11°C) cooler than the shotcrete surface at the time the water and shotcrete come into contact.

2.1.5 Admixtures—Admixtures may be used in shotcrete construction to enhance certain properties for special shotcrete applications and for certain conditions of shotcrete placement. Admixtures not previously used in shotcrete should be tested during preconstruction testing before large-scale use to determine that the expected advantages can be obtained with no adverse effects. Admixtures should meet the requirements of **ASTM C1141/C1141M**. Admixtures for shotcrete generally fall into five categories: accelerators, air entrainment, water reducers, retarders, and rheology modifiers. Admixtures can be either powder or liquid (2.6.1.3).

2.1.5.1 Accelerators—Accelerators can be divided into two general categories: chemical-set accelerators and rheology modifiers.

2.1.5.1.1 Chemical-set accelerators—Chemical-set accelerators are used in both the dry-mix and wet-mix processes to:

- (a) Enhance the maximum buildup thickness by increasing the early stiffness, which increases productivity by reducing the number of passes
- (b) Reduce the incidence of shotcrete fallouts, thus increasing security in overhead areas
- (c) Accelerate the hydration process, thereby increasing early strength development

The major types of chemical set accelerators are sodium and potassium carbonates, and calcium aluminates. Organic compounds, such as triethanolamine, can also be used in formulating chemical set accelerators. While the use of chemical set accelerators is usually quite effective, some may reduce the ultimate strength and durability. For this reason, they should always be thoroughly evaluated before use, and dosage rates should be kept to a minimum in the final mixture.

Calcium chloride has been used as an accelerator but is not recommended for use in reinforced structures because calcium chloride promotes corrosion.

The effect of different accelerating admixtures can vary widely. Certain types of accelerators can significantly reduce the setting time (initial setting times as rapid as a few minutes are common). This property is useful in tunneling or applications that need to quickly seal surfaces against water leakage to help prevent shale or other materials from slaking caused by exposure to air and moisture, and to quickly build up layers of shotcrete applied to vertical and overhead surfaces.

Other types of accelerators cause both a decrease in the initial setting time and an increase in the rate of strength development. These accelerators are referred to as early-strength accelerators and are particularly helpful in tunnels and mines where immediate support is required.

The choice of a particular type of product should be based on the desired performance. Generally, the greater

the effect of the admixture on the shotcrete setting time and early strength, the greater the reduction will be to long-term strength and durability. Also, the effect of a given accelerator can be cement-specific. **ASTM C1141/C1141M** tests for compatibility of shotcrete accelerators and portland cement. **ASTM C403/C403M** can determine the rate of setting and early strength development of accelerated shotcrete. Accelerators are typically caustic or acidic and should be handled with particular care. Conduct preconstruction testing to verify compatibility.

2.1.5.2 Rheology modifiers—Rheology modifiers change the rheology of the mixture, not the cement hydration, making the mixture stiffer. Examples include sodium, potassium or lithium silicate (water glasses), and precipitated colloidal silica. Rheology modifiers promote a rapid stiffening of the material, therefore allowing enhanced buildup thickness. They are not, however, efficient at increasing the rate of strength development at early ages because they do not promote early chemical reaction in hydrating portland cement. Rheology modifiers and accelerators can be highly incompatible and should not be mixed in the same mixture. Special tests, such as needle penetration tests, are available to determine the rate of setting and early strength development of accelerated shotcrete (**Beaupré et al. 2004**).

2.1.5.3 Air entrainment—Adding air-entraining admixtures (AEAs) improves concrete's ability to resist repeated freezing and thawing. Wet-mix shotcrete with 3 to 4% air entrainment has satisfactory durability and has been shown to provide excellent resistance to saturated freezing-and-thawing conditions. AEAs should meet the requirements of **ASTM C1141/C1141M**. Testing of in-place air content, if required, can be done in accordance with **ASTM C173/C173M** or **ASTM C231/C231M**.

In dry-mix shotcrete, air entrainment is typically not used except in severe saturated freezing-and-thawing conditions. Some contractors, however, have had good results by adding AEA to dry-mix shotcrete to improve resistance to freezing and thawing and deicing-chemical scaling. Liquid AEA can be used when introduced with the mixing water on site, which is usually done by metering the AEA into the water supply used for shotcreting. Non-liquid or powdered AEA have also been proven to be an effective method of entraining air in dry-mix shotcrete. When prepackaged dry material is used, powdered AEA can be preblended with the other dry ingredients of the shotcrete mixture and weigh-batched according to the cementitious content. When the admixture dosage at the source is consistent and not a function of the water introduced at the nozzle to get the desired mixture consistency, a consistent air-void system can then be expected (Section 2.4.4).

2.1.5.4 Water-reducing admixtures—Water-reducing admixtures are commonly used to produce shotcrete material for the wet-mix process. As in regular concrete application, these types of admixtures allow the mixture to achieve and maintain the desired consistency while keeping the proper *w/cm*. Water-reducing admixtures for wet-mix shotcrete should conform to **ASTM C1141/C1141M** (Section 3).

Such admixtures are normally not used in dry-mix shotcrete. Many water reducers also retard hydration.

2.1.5.5 Retarding and hydration control—Retarding admixtures are used when delayed set is desired, and they should conform to **ASTM C1141/C1141M**. Retarding admixtures delay the set and allow for extended times from batching to final placement without affecting the characteristics of the hardened shotcrete. Special hydration-controlling admixtures, which delay the time of set from several hours to as much as several days, are also available. Such shotcrete is treated with special activators, which are added at the nozzle in much the same way as accelerators, to reactivate the hydration process.

2.1.5.5.1 Retarders—Retarders are typically lignin-, borax-, or sugar-based, and used in dosage rates of 2 to 9 fl oz per 100 lb (130 to 590 mL per 100 kg) of cementitious materials to slow the hydration process of portland cement. Retarders increase the useful workable time of a shotcrete mixture. Retarders, used at their maximum dosage, can reduce slump loss for up to 3 hours without affecting the shotcrete mixture's normal plastic or hardened properties.

2.1.5.5.2 Hydration control admixtures—Hydration control admixtures (HCAs) are typically chelating agents such as carboxylic acids or phosphorous containing organic acid salts and are used in dosage rates of 2 to 60 fl oz per 100 lb (130 to 3900 mL per 100 kg) of cementitious material. HCAs suspend the hydration process of portland cement, thereby preventing the shotcrete mixture from reaching initial set. Water and ions required for hydration are blocked to prevent cement surface activity, effectively halting the hydration process. Hydration control times are regulated by dosage rates. HCAs can maintain the consistency of wet-mix shotcrete for the required delivery and placement duration and provide time to clean up hoses and pumps and deal with plugs. Shotcrete mixtures treated with HCAs resume normal hydration properties as the dosage effects subside or when activated by the addition of an accelerating admixture. HCAs can be added to the mixture water or added in the same manner as liquid admixtures during batching. Dosage rates will depend on the specific material, ambient temperature, and the stabilization period. HCAs are commonly used for wet-mix shotcrete placement to delay initial set in hot-weather conditions. HCAs at high dosage rates have been used in tunneling operations to delay initial set for up to 72 hours. Wet-mix shotcrete can be treated with HCAs without affecting the mixture normal plastic or hardened properties.

2.1.6 Fiber—Refer to 2.1.7.4.

2.1.7 Reinforcement

2.1.7.1 Reinforcing bars—Shotcrete construction requires care in the spacing and arrangement of reinforcement because heavy concentrations of steel interfere with the shotcrete stream. As bar size increases or if the spacing decreases, the nozzleman's skill becomes increasingly important to ensure complete encasement without significant voids. Bar lap splices, couplers, number of curtains, and depth of section also interfere with the shotcrete stream, which further complicates encasement and requires careful

attention by the nozzleman. Lap bar splices create a large obstruction that becomes difficult to encase, so lap bar splices should be avoided where possible (**Section 3.1.4.2**). Reinforcement should be free from oil, loose rust, mill scale, dust, or other surface deposits that may affect its bond to the shotcrete. Wire tie knots should be reduced in size to minimize obstruction to the shotcrete stream.

2.1.7.2 Welded wire reinforcement—Should conform to **ASTM A1064/A1064M** and may be uncoated or galvanized. Commonly used fabric gauges are W2 or W1.4 (MW9.1 or MW12.8) wire, spaced 4 in. (100 mm) in both directions. Galvanized mesh is sometimes specified to reduce the possibility of corrosion of the mesh in aggressive environments. Care, however, should be taken when specifying the use of galvanized mesh to avoid creating other problems.

2.1.7.3 Coated reinforcement (epoxy or galvanized)—Shotcrete, particularly dry-mix, is abrasive, so testing is recommended before using coated reinforcement. A preconstruction mockup should be shot to determine the effect of the shotcrete process on the coating by washing off the freshly applied shotcrete and examining the coating.

2.1.7.4 Fiber reinforcement—Fibers for use in shotcrete can be made of steel, glass, synthetic polymers, and natural materials (Fig. 2.1.7.4a and 2.1.7.4b). Steel and synthetic fibers are commonly used with shotcrete. Fibers for use in shotcrete are generally divided into two groups by their diameter. Fibers with equivalent diameters greater than 0.012 in. (0.3 mm) are known as macrofibers, and fibers with



Fig. 2.1.7.4a—Macrofibers.



Fig. 2.1.7.4b—Fibers for use in shotcrete.

equivalent diameters less than 0.012 in. (0.3 mm) are known as microfibers. **ASTM C1116/C1116M** defines the required properties of fiber-reinforced shotcrete (FRS) and fibers used in shotcrete. Alkali-resistant glass fibers have also been used successfully in shotcrete. Detailed information on FRS can be found in **ACI PRC-506.1** (Sections 2.3 and 2.4.8).

2.1.8 Curing compounds—Curing compounds are typically not used if subsequent layers of shotcrete are to be placed because the curing compound may interfere with bond between layers of shotcrete.

2.1.8.1 Sheet material—Sheet material should meet the requirements of **ASTM C171**.

2.1.8.2 Curing compounds—All form coatings and membrane-curing compounds or floor sealers should conform to the air-quality regulations applicable at the project site, in **ASTM C309** or **C1315**, and in local code requirements. Products that cannot be guaranteed by the manufacturer to conform, whether or not specified by product designation, should not be used. When water curing is not possible, many shotcrete contractors apply curing compounds but apply twice the coverage recommended by manufacturers because shotcrete surfaces are usually rougher than cast-in-place concrete surfaces, thus requiring a greater amount of curing compound. Preconstruction testing should be conducted prior to use.

2.1.8.3 Architectural finish—Some curing compounds may stain the concrete finish. Preconstruction testing should be conducted prior to use.

2.1.8.4 Surface evaporation retardants—Surface evaporation retardants are polymers mixed with water and applied to the surface to retard surface evaporation. Follow the manufacturer's recommendations.

2.1.9 Bonding compounds—Bonding compounds are not normally used with shotcrete because the bond of shotcrete to properly prepared substrates is excellent. Bonding compounds can act as bond breakers if careful attention is not paid to preparation and the timing of placement of subsequent shotcrete.

2.2—Packaged shotcrete materials

Prepackaged material suppliers combine dry aggregate cementitious materials, fibers, admixtures, and dry admixtures in accordance with buyer's requirements. Packaging sizes vary from 50 to 4000 lb (25 to 1800 kg). The materials should comply with **ASTM C1480/C1480M**. To use prepackaged material for dry-mix shotcrete, the mixture is typically predampened to reduce dusting prior to conveying to the nozzle. If an accelerator is part of the prepackaged mixture, check with the manufacturer before using a predampener. For use with wet-mix shotcrete, the required amount of water is added and the complete mixture is thoroughly mixed before being pumped to the nozzle.

2.3—Fiber-reinforced shotcrete

FRS is an efficient method of reinforcing hard-to-reach overhead or vertical concrete elements. Fiber reinforcement gives shotcrete toughness and load-bearing capacity after cracking. It also helps control restrained shrinkage cracking

and improves impact resistance. Fibers are typically synthetic or steel (Section 2.1.7.4). Synthetic microfibers may reduce the susceptibility of shotcrete to plastic shrinkage cracking. At higher addition rates, steel or synthetic macrofibers can improve performance. Shotcrete allows FRS to be placed in multiple thin layers with each succeeding layer flattening the previous layer, causing fibers to lay roughly parallel to the surface so they are more effective than the random distribution that occurs in fiber-reinforced concrete. FRS may have greater rebound than normal aggregate shotcrete, particularly dry-mix shotcrete. As the aggregate rebound increases, the amount of fiber rebounding is proportionally higher. Special care, and sometimes special equipment, may be required in adding fibers to the shotcrete mixture to prevent clumping or kinking of the fibers and to ensure that they are properly proportioned (refer to Sections 2.1.7.4 and 2.4.8, and **ACI PRC-506.1**).

2.3.1 Dosage recommendations—The following are general dosage recommendations for steel and synthetic fibers. Adding fibers to a shotcrete mixture may require adjustment to the mixture design.

(a) Steel fibers between 0.7 and 1.4 in. (18 and 36 mm) long with dosage rates up to 0.75% by volume of the shotcrete (approximately 100 lb/yd³ [59.5 kg/m³]) can reduce crack propagation, increase flexural behavior, and improve toughness and impact resistance. For wet-mix shotcrete, steel fiber quantities used are in the range of 20 to 80 lb/yd³ (12 to 47 kg/m³); for dry-mix shotcrete, steel fiber quantities may be slightly higher up to 1% by volume (approximately 131 lb/yd³ [78 kg/m³]). Steel fibers should conform to **ASTM A820/A820M**.

(b) Synthetic fibers for shotcrete are commonly polypropylene, either macrofiber or microfiber. Macrofiber quantities are usually in the range of 5 to 12 lb/yd³ (3 to 7 kg/m³) and microfiber quantities are usually in the range of 1 to 2 lb/yd³ (0.6 to 1.2 kg/m³). One percent by volume is approximately 15 lb/yd³ (9 kg/m³). Synthetic fibers should conform to **ASTM D7508/D7508M**.

2.4—Shotcrete properties

2.4.1 Introduction—There are many different types of mixtures applied by shotcreting, including plain, fiber-reinforced, and high-performance. The different types have different hardened properties.

The mixture composition should be such that the in-place hardened shotcrete will develop acceptable mechanical and physical properties. As a general rule, the mixture composition will affect hardened shotcrete properties in the same way as normal cast-in-place concrete. Effects associated with the shooting process, such as consolidation, air content, rebound, and fiber orientation, however, may affect the hardened shotcrete properties (**Lorman 1968**).

The w/cm is the key parameter for all shotcrete, as is the initial cementitious material-aggregate ratio for dry-mix shotcrete. Reducing the w/cm enhances most properties of shotcrete, including strength, permeability, and durability. The presence of accelerators, silica fume, and other admixtures modifies physical properties, especially permeability and

durability. High-performance shotcrete, which can include properties such as high compressive strength, low permeability, high durability, and heat or chemical resistance, can be achieved with supplemental cementitious materials and special admixtures. As with normal cast-in-place concrete, proper curing is important and improves the mechanical and physical performance of hardened shotcrete.

2.4.2 Compressive strength—The default compressive strength for structural shotcrete is 4000 psi (28 MPa). The compressive strength of structural shotcrete depends on the cementitious materials-to-aggregate ratio (*cm:agg*) and *w/cm*. Shotcrete compressive strengths of 4000 to 6000 psi (28 to 41 MPa) are typical. Reducing the *w/cm* using high-range water-reducing admixtures, in the case of wet-mix shotcrete, and adding silica fume can produce high-strength shotcrete with strengths exceeding 12,000 psi (83 MPa).

Early-age strength development is often more important than the ultimate strength in rehabilitation work, tunnels, and underground supports. In these cases, accelerators are often used to reduce setting time and improve early strength development. The addition of accelerators, however, will, in most cases, reduce long-term strength, even as early as 28 days, and reduce durability compared with a non-accelerated shotcrete of the same composition. These effects are usually proportional to the accelerator dosage and are affected by the chemical composition of accelerators (Gebler et al. 1992; Jolin et al. 1997; Schutz 1982) (Section 2.1.5.1).

2.4.3 Flexural properties—Shotcrete exhibits the same flexural properties as cast-in-place concrete. Traditionally, welded-wire reinforcement has been used in shotcrete tunnel linings to provide toughness to the shotcrete lining. Welded-wire reinforcement, however, is increasingly being replaced by steel or macro-synthetic fibers to provide flexural strength (refer to Section 2.4.8 and ACI 506.4R).

2.4.4 Air content (durability)—Beaupré et al. (1994), Glassgold (1989), Morgan et al. (1988), and Seegebrecht et al. (1989) all discuss shotcrete durability, especially freezing-and-thawing resistance and salt-scaling resistance of shotcrete. Durability and freezing-and-thawing resistance of shotcrete, like concrete, is dependent on three major factors: *w/cm*, cementitious materials, and quality of the air-void system (especially the spacing factor) as determined in accordance with ASTM C457/C457M.

Critically saturated shotcrete, both wet- and dry-mix with a *w/cm* less than 0.45, an entrained air-void system with minimum air content of 3% in the in-place shotcrete, and a maximum air-void spacing factor of 0.01 in. (0.254 mm) performs well in resisting rapid freezing-and-thawing cycles (ASTM C666/C666M) and is resistant to deicer salt scaling (ASTM C672/C672M) (Section 2.1.5.3).

The shotcrete process both entraps some air on impact and loses entrained air so that an air test of the in-place mixture measures both entrapped air and the remaining entrained air. Entrapped voids are significantly larger than entrained voids and increase the in-place air content without offering any significant protection against scaling due to freezing in the presence of deicing salts. Only entrained air provides freezing-and-thawing resistance.

Because of the loss of entrained air during the shotcrete process, it is difficult to achieve greater than 5% air content in the in-place shotcrete. To get at least 3% air in the in-place shotcrete, a minimum of 6% entrained air is needed in the shotcrete mixture before pumping. Increasing air content in the shotcrete mixture improves pumpability of wet-mix and reduces shotcrete rebound. Air contents greater than 10% have been found to complicate pumping.

Dry-mix shotcrete without air entrainment, when tested for resistance to rapid freezing and thawing per ASTM C666/C666M, has demonstrated good durability and has performed well in freezing-and-thawing environments due to the low *w/cm* (less than 0.4).

For the dry-mix process, it is possible to improve the quality of the air-void system by adding an air-entraining admixture to the mixing water or adding a dry, powdered, air-entraining admixture to the shotcrete mixture.

2.4.5 Water-soluble chloride ion content in shotcrete mixture—For corrosion protection of the reinforcement in the shotcrete, maximum water-soluble chloride ion concentration in hardened shotcrete at ages from 28 to 42 days should not exceed the limits shown in Table 2.4.5. When testing is performed to determine water-soluble chlorine ion content, test procedures should conform to ASTM C1218/C1218M. Also refer to ACI 318 and ACI 350 for further guidance on corrosion protection of the reinforcement.

2.4.6 Limitations on supplementary cementitious materials—As with all concrete mixtures, the addition or substitution of supplementary cementitious materials will change the characteristic of the mixture and should only be done with caution after considering the impact on fresh and hardened properties. ACI 318 and ACI 350 provide limits on the use of supplementary cementitious materials in concrete. These limits vary depending on exposure conditions. Preconstruction testing should be conducted prior to use.

2.4.7 Boiled absorption and volume of permeable voids (porosity)—One method to measure porosity is to conduct a boiled water absorption (BWA) or volume of permeable voids (VPV) test (ASTM C642). Both BWA and VPV tests provide an indicator of the porosity of the shotcrete and are conducted on hardened shotcrete. The results may provide an overall indication of the quality of the placement of the shotcrete, especially in dry-mix shotcrete where the results are largely influenced by the *w/cm*. The absorption value and the volume of permeable voids are useful in identifying poorly compacted shotcrete or shotcrete with a weak or

Table 2.4.5—Maximum water-soluble chloride-ion concentration in concrete for corrosion protection of reinforcement percentage by weight of cement*

Prestressed concrete	0.06
Reinforced concrete exposed to chloride in service	0.15
Reinforced concrete that will be dry or protected from moisture in service	1.0
Reinforced concrete exposed to moisture, but no external source of chlorides	0.5

*Adapted from ACI 318.

damaged microstructure, which may be due to overdosing the mixture with an accelerator admixture.

Results of BWA tests can vary not only on quality of placement, but also on the absorptive characteristics of the aggregate and paste volume. Typical BWA values for quality shotcrete with nonporous aggregate with normal cement factors range from 6 to 8%, and VPV results range from 14 to 17%. When somewhat porous aggregates are used, such as limestone, the BWA values may range up to 9% with high-quality shotcrete. Using lightweight aggregates with a higher absorption also produces higher BWA results. The absorption of a shotcrete specimen is usually proportional to its w/cm . A low w/cm will yield a relatively low volume of permeable voids or low absorption values, which is an indication of a high-quality shotcrete. A sand-cementitious shotcrete mixture can be expected to have higher-than-typical BWA values due to a higher paste volume. A mixture shot too dry, however, may yield a relatively high volume of permeable voids or high absorption values due to the stiffness of the plastic shotcrete. Impact velocity is another important parameter that influences the porosity of the hardened shotcrete; insufficient impact velocity will not provide sufficient consolidation. If BWA is specified, perform preconstruction tests along with compressive strength tests using cast samples of the shotcrete mixture to provide a baseline value for the material. High compressive strength results and high absorption results may indicate good compaction, but absorptive aggregate or high paste content.

Set accelerators may have a detrimental effect on the porosity of shotcrete, usually due to the flash-setting effect of the admixture, which diminishes the self-consolidating effect of shotcrete. The influence of different accelerators, however, will vary and should be checked by conducting preconstruction testing. Proper dosing of accelerators is critical.

2.4.8 Flexural strength and toughness of fiber-reinforced shotcrete—Macrofibers (steel or synthetic) are added to increase the post-cracking flexural strength (the ability to carry flexural loads after cracking). In general, fibers are not added to shotcrete to increase the flexural strength of shotcrete. This post-crack performance is measured as energy absorbed after cracking. Two ASTM test methods were developed to measure the toughness and strength of FRS. **ASTM C1609/C1609M** is a flexural beam test method that determines both strength and toughness. **ASTM C1550** is also a flexural test that determines flexural toughness, using a round panel specimen. The ASTM C1609/C1609M beam test method has the advantage of resulting in material flexural

strengths that can be used in engineering design and serviceability considerations. The ASTM C1550 round panel test method has the advantage of low variability. Correlations between beam test results and panel test results are not valid. The beam tests and round panel tests are both used in normal practice and for quality assurance/quality control (QA/QC) during construction to determine the residual strengths available from given fibers and dosages (**ACI PRC-506.1**). An additional test, used for its easier laboratory procedure, is **ASTM C1399/C1399M**, where residual strength is evaluated for FRS.

2.4.9 Bond strength—Shotcrete is physically driven onto the receiving surface by the high velocity of the impacting particles. Studies focusing on the bond qualities of shotcrete have proven that high-velocity placement to a sound substrate surface with an adequate roughness profile provides a durable bond. Shotcrete applied at high velocity to a substrate creates bonding conditions that are unique to the shotcrete process. Impact energy at the substrate surface effectively embeds a rich, tightly compacted paste layer within the surface irregularities of the bond plane. Shotcrete applied to a clean, roughened concrete substrate in proper moisture conditions can form a bond that is stronger than the cohesive strength of the underlying layer.

Bond strength is usually measured by shear or direct tension using a pulloff test. Properly applied shotcrete with sufficient consolidation on a properly prepared substrate usually develops bond strength of over 145 psi (1 MPa). **ASTM C1583/C1583M** is used to determine bond strength of shotcrete substrates.

Bond-strength test results for dry-mix and wet-mix shotcrete conducted on different prepared concrete substrates indicated that the mixture composition of shotcrete has less influence on bond than surface preparation. Best results were obtained with hydromilling, sandblasting alone, or chipping with chipping hammers followed by sandblasting (Table 2.4.9). Other types of surface preparation (grinding and chipping with chipping hammers without sandblasting) resulted in either lower bond strength or a reduction in bond durability (reduction of bond strength with time). The moisture condition of the substrate at the time of application of the shotcrete is also important. Best bond is achieved on a saturated surface-dry (SSD) substrate. Excessively dry or wet substrate surfaces at the time of shotcrete application will result in reduced bond strength.

Brooming between layers of shotcrete while still plastic breaks up surface laitance, roughens the surface, and removes or imbeds overspray. All these actions improve

Table 2.4.9—Influence of concrete surface preparation on shotcrete tensile bond strength, psi (MPa)

Type of shotcrete	Hydromilling*	Sandblasting	Grinding	Chipping	Chipping and sandblasting
Dry-mix	230 (1.6)	290 (2.0)	30 (0.2)	190 (1.3)	245 (1.7)
Dry-mix + silica fume + fibers	290 (2.0)	290 (2.0)	115 (0.8)	160 (1.1)	275 (1.9)
Wet-mix	230 (1.6)	—	—	—	—

*The surface was prepared by hydromilling to remove the surface skin of concrete.

Note: Results are a compilation of bond test from several projects. Most failures occurred in the substrate concrete. There were 11 tests and the average tensile bond strength was 200 psi (1.5 MPa).