Guide to Shotcrete

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

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Reported by ACI Committee 506

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James A. Ragland, Secretary

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*Subcommittee Chair who produced this guide.

Consulting members

Jean-Francois Dufour
Merlyn Isaak
Richard A. Kaden
Dudley R. Morgan
H. Celik Ozyildirim
Harvey W. Parker

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 proportion; 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, however, and 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.

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 a number of 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 506.1R).

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 rational 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 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).

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 percent 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.

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 μm)	25 to 60	20 to 35
No. 50 (300 μm)	10 to 30	8 to 20
No. 100 (150 μm)	2 to 10	2 to 10

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

1.1.1.3 *Comparison of processes*—Either process can produce shotcrete suitable for normal 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.

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 maximum-size 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 impact 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 percent 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 is 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 0.3 and 1.0 percent 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 (2.1.7.4, 2.3, and 2.4.8).

1.2—Definitions

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.

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: See Part 7—References

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 *Reinforcement mill certificates*—Refer to 2.1.7.

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

1.4.1.14 *Hydration control admixtures*—Refer to 2.1.5.5 or 2.1.5.5.2.

1.4.1.15 *Repair procedures*—Refer to 3.9.

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

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

1.5—Preconstruction testing by contractor

Preconstruction testing should be considered on large, complex jobs if previous data are not available, if properties 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, 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 core the panel when necessary to check the soundness and uniformity of the material. All cut and cored 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

Fig. 1.5.1a—Mockup.

Fig 1.5.1b—Crew shooting mockup panel.

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 percent 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