Guide to Shotcrete

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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 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.