

Guide to Shotcrete

Reported by ACI Committee 506

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This guide 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, and finished shotcrete acceptance tests, are also discussed.

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

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CHAPTER 1—GENERAL

1.1—Introduction

Shotcrete has grown into 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. The guide was originally prepared to replace “Recommended Practice for Shotcreting” (ACI 506-66, Revised 1983).

1.2—Scope

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 control. New construction, repair, linings, coatings, refractories, underground support, and other special applications are also discussed. An appendix on suggested methods of payment is included. Procedures vary from one region to another, and adjustments may be required to meet the needs of a particular project. No attempt is made to provide guidelines for the design of shotcrete installations.

1.3—History

In 1910, a double-chambered cement gun, 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 Gunitite. In the ensuing years, trademarks such as Guncrete, Pneucrete, Blastcrete, Bloccrete, Jetcrete, and the terms “pneumatically applied mortar or concrete” and “sprayed concrete” were introduced to describe similar processes. The early 1930s saw the generic term “shotcrete” introduced by the American Railway Engineering Association to describe the Gunitite 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 (ACI Committee 506 1966).

The 1950s saw the introduction of dry-mix guns, which applied mixtures containing coarse aggregate; wet-mix shotcrete equipment; and the rotary gun, a continuous feed device. Many improvements were made to wet-mix equipment and materials in the 1970s and 1980s. These improvements allowed pumping low-slump concrete longer distances at greater volumes. These innovations enhanced the utility, flexibility, and general effectiveness of the process. The development of centrifugally applied concrete and low-pressure, low-velocity wet-process mortar and concrete are not considered shotcrete in this guide because they do not comply with the current definition of shotcrete or they do not achieve sufficient compaction (ACI Compilation No. 6 1987).

1.4—Definitions

The following definitions cover terms used in shotcreting:

air ring—a perforated manifold in the nozzle of wet-mix shotcrete equipment through which high-pressure air is introduced into the material flow.

air-water jet—a high-velocity jet of air and water used for scouring surfaces in preparation for the next layer of shotcrete.

alignment wire—see **ground wire**.

blowpipe—air jet operated by a nozzle operator's helper in shotcrete shooting to assist in keeping rebound or other loose material out of the work. Also known as an air lance.

buildup—thickness of the freshly applied shotcrete.

bulking—increase in volume of sand in a moist condition over the same quantity in a dry condition.

brooming—a finishing procedure in which a broom is pulled across the shotcrete surface to roughen the surface.

coarse-aggregate shotcrete—shotcrete with a nominal coarse-aggregate size larger than 1/4 in. (5 mm).

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

conventional shotcrete—shotcrete composed only of portland cement and normalweight aggregates.

conveying hose—see **delivery hose**.

cutting screed—sharp-edged tool used to trim shotcrete to finish outline; see also **rod**.

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.

delivery hose—hose through which shotcrete materials pass on their way to the nozzle; also known as material hose or conveying hose.

dry-mix shotcrete—shotcrete in which most of the mixing water is added at the nozzle.

entrained air—microscopic air bubbles intentionally incorporated in mortar or concrete during mixing, usually by use of a surface-active agent; typically between 0.0004 in. (10 μ m) and 0.04 in. (1 mm) in diameter and spherical or nearly so.

entrapped air—air voids in concrete that are not purposely entrained and are significantly larger than 0.04 in. (1 mm), or larger in size than entrained air voids and are not contributory to resisting freezing-and-thawing action.

feed wheel—material distributor or regulator in certain types of shotcrete delivery equipment.

fiber—short, discrete pieces of steel or synthetic material added to shotcrete as reinforcement.

finish coat—final thin coat of shotcrete preparatory to hand finishing; see also **flash coat**.

finisher—craftsman that trims and finishes the surface of the shotcrete; see also **rodman**.

flash coat—thin shotcrete coat applied from a distance greater than normal for use as a final coat or for finishing; also called flashing.

ground wire—small-gauge, high-strength steel wire used to establish line and grade for shotcrete work; also called alignment wire, screed wire, or shooting wire.

gun—dry-mix shotcrete delivery equipment.

gun finish—undisturbed final layer of shotcrete as applied from a nozzle without hand finishing.

gun operator—craftsman on dry-mix shotcreting crew who operates delivery equipment.

gunite—term sometimes used for dry-mix shotcrete.

gunning—the act of applying shotcrete; shotcreting.

Hamm tip—a flared shotcrete nozzle with a larger diameter at midpoint than either inlet or outlet.

hydronozzle—a special prewetting and mixing nozzle consisting of a short length of delivery hose inserted between the nozzle body and nozzle tip; also called premixing nozzle.

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

laitance—a layer of weak and nondurable material containing cement and fines from aggregates, brought by bleeding water to the surface of overwet shotcrete; the amount is generally increased by overworking or over-manipulating concrete at the surface by improper finishing or by job traffic.

lance—an extended nozzle of various configurations consisting of a length of metal pipe with nozzle and body (or bodies) used to shoot shotcrete refractory material in areas of elevated temperature.

material hose—see **delivery hose**.

nozzle—attachment at end of delivery hose from which shotcrete is projected at high velocity.

nozzle body—a 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.

nozzle liner—replaceable insert in nozzle tip, usually rubber, to reduce wear.

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

nozzle velocity—the velocity of shotcrete material particles at exit from nozzle, in ft/s (m/s).

overspray—shotcrete material deposited away from intended receiving surface.

pass—distribution of stream of materials over the receiving surface during shotcreting. A layer of shotcrete is built up by making several passes.

pneumatic feed—shotcrete delivery equipment in which a pressurized air stream conveys material.

pneumatically applied concrete—see **shotcrete**.

pneumatically applied mortar—see **shotcrete**.

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, adding water to the aggregate before mixing to bring its moisture content to a specified amount, usually 3 to 6%.

prewetting—in the dry-mix process, adding a portion of mixing water to shotcrete materials in the delivery hose at some distance before the nozzle.

puddling—placement of shotcrete where air pressure is decreased and water content is increased, usually an undesirable method of shotcreting.

pump—wet-mix delivery equipment.

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

rebound—shotcrete that bounces away from the surface against which the shotcrete is being projected.

rod—sharp-edged cutting screed used to trim shotcrete to forms or ground wires.

rodman—craftsman on the shotcrete crew who uses a rod or other tools to trim and finish the shotcrete.

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.

sagging—see **sloughing**.

sand lens—see **sand pocket**.

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

scratch coat—shotcrete layers that are placed before the finish coat.

screed wire—see **ground wire**.

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

shooting—act of applying shotcrete; see also **gunning**.

shotcrete—mortar or concrete pneumatically projected at high velocity onto a surface.

sloughing—subsidence of shotcrete, generally due to excessive water in the mixture; also called sagging.

slugging—pulsating or intermittent flow of shotcrete material.

water ring—a perforated manifold in the nozzle body of dry-mix shotcrete equipment through which water is added to the materials.

w/cm—water-to-cementitious material ratio.

wet-mix shotcrete—shotcrete in which all of the ingredients, including water, are mixed before introduction into the delivery hose; compressed air is introduced to the material flow at the nozzle.

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

1.5—Shotcreting processes

Shotcreting is classified according to the process used (wet-mix or dry-mix) and the size of aggregate used (coarse or fine). Refer to Table 1.1 for fine-aggregate grading (No. 1) and coarse-aggregate grading (No. 2).

1.5.1 Dry-mix process—The dry-mix process consists of five steps:

- 1. All ingredients, except water, are thoroughly mixed;
- 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 use 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 mixed with the other ingredients; and

Table 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 1.2—Comparison of dry-mix and wet-mix processes

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

5. The material is jetted from the nozzle at high velocity onto the surface to be shotcreted.

1.5.2 Wet-mix process—The wet-mix process consists of five steps:

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

1.5.3 Comparison of the 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 1.2 gives differences in operational features and other properties that may merit consideration.

1.5.4 Coarse-aggregate shotcrete—There are four reasons for adding coarse aggregate to shotcrete:

- 1. The reduced surface area of coarse aggregate versus fine aggregate permits lower water content;
- 2. Coarse aggregate reduces drying shrinkage by reducing fine aggregate content;

3. The addition of coarse aggregate may improve pumpability for wet-mix;

4. The impact of coarse aggregate into plastic shotcrete improves the in-place density; and

5. The economy of the mixture may be improved.

For both the dry-mix and wet-mix processes, however, coarse-aggregate shotcrete with more than 30% coarse aggregate has greater rebound, is more difficult to finish, and cannot be used for thin layers. Coarse-aggregate shotcrete requires the use of a larger-diameter hose and creates craters in the plastic shotcrete when shot at high velocity.

1.6—Properties

There are many different types of mixtures applied by shotcreting, including plain, silica fume, fiber-reinforced, high-strength, 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 concrete. Effects associated with the shooting process, such as compaction, rebound, and fiber orientation, however, may affect the hardened shotcrete properties (Lorman 1968).

The w/cm is the key parameter for wet-mix shotcrete, as is the initial cement-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, or other pozzolans modifies physical properties, especially permeability and durability. The use of an air-entraining admixture improves shotcrete's resistance to freezing and thawing, while the use of fibers improves toughness. As with normal cast-in-place concrete, proper curing is important and always improves the mechanical and physical performance of shotcrete.

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 special admixtures and materials such as silica fume.

1.6.1 Compressive strength—The compressive strength of dry-mix shotcrete depends to a large extent on the cement-aggregate ratio. Compressive strengths up to 12,000 psi (85 MPa) can be produced while strengths of 6000 to 7000 psi (40 to 50 MPa) are common.

Reducing the w/cm , using high-range water-reducing admixtures, and adding silica fume can produce high-strength wet-mix shotcrete. Strengths over 14,000 psi (100 MPa) have been reported for dry-mix. Usually the strength of wet-mix shotcrete is between 4000 and 7000 psi (30 to 50 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 improve early strength development. They may, however, reduce long-term strength, even as early as 28 days, and durability compared with a non-accelerated shotcrete of the same composition. These effects are usually proportional to the accelerator dosage, or are affected by the chemical

Table 1.3—Influence of surface preparation on tensile bond strength, psi (MPa)

Type of shotcrete	Hydro-milling*	Sand-blasting	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. Notes: Results are a compilation of bond test from several projects. Most failures occurred in the substrate concrete. There were 18 tests, and the average tensile bond strength was 200 psi (1.5 MPa).

composition of accelerators (Gebler et al. 1997; Jolin et al. 1997; Schutz 1982).

1.6.2 Flexural properties—Traditionally, welded-wire fabric was used in shotcrete tunnel linings to provide ductility to the shotcrete lining. Now welded-wire reinforcement is increasingly being replaced by steel or synthetic fibers. Fiber reinforcement gives shotcrete toughness and load-bearing capacity after cracking. It also helps control restrained shrinkage cracking and improves impact resistance. Post-cracking behavior can be evaluated by flexural toughness tests such as ASTM C 1018.

1.6.3 Bond strength—Because shotcrete is physically driven onto the receiving surface, it usually exhibits good bond with concrete, masonry, rock, steel, and many other materials. Bond strength is usually measured by shear or direct tension using a pull-off test. Shotcrete should develop a minimum tensile bond strength of 100 psi (0.7 MPa). Properly applied shotcrete with sufficient compaction on a well-prepared substrate usually develops a bond strength of over 145 psi (1 MPa).

Bond-strength test results for measurements 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 1.3). The other types of surface preparation (grinding, 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 substrate. Excessively dry or wet substrate surfaces at the time of shotcrete application reduce bond strength. Brooming between layers of shotcrete breaks up laitance, removes or imbeds overspray, and these practices improve bond. It is also important that the substrate surface be kept clean between applications (Talbot et al. 1994).

1.6.4 Shrinkage—Shrinkage is an important parameter with respect to potential cracking and bond durability, especially if shotcrete is used to repair concrete structures. The drying shrinkage of shotcrete varies with the mixture proportion, but generally falls within the range of 0.06 and 0.10% at 3 months, as measured by ASTM C 157. Shrinkage is typically greater in shotcrete than most conventional concretes, mainly because shotcrete has less coarse aggregate and more cementitious



Fig. 1.1—Elevated prestressed shotcrete water storage tank.

material and water. The use of accelerators tends to increase shrinkage and the potential for cracking.

1.6.5 Resistance to freezing and thawing—There are many references and compilations concerning shotcrete durability, especially freezing-and-thawing resistance of shotcrete and salt-scaling resistance of shotcrete (Beaupre et al. 1994; Glassgold 1989; Morgan et al. 1988; Seegebrecht et al. 1989). The freezing-and-thawing resistance of shotcrete, as it is for normal concrete, is strongly dependent on the w/cm and on the quality of the air void system, especially the entrained-air-void content and spacing factor determined in accordance with ASTM C 457.

Critically saturated wet-mix shotcrete requires an entrained air-void system with a minimum air content of 4% with a maximum air void spacing factor of 0.001 in. (0.30 mm) to resist rapid freezing-and-thawing cycles (ASTM C 666). Wet-mix shotcrete is normally only resistant to deicer salt scaling (ASTM C 672) if an air-entraining admixture is used and if the in-place w/cm is less than 0.45.

When wet-mix shotcrete is placed, the majority of entrained air is lost during shooting. To have sufficient entrained air in the in-place material per the committee's consensus, wet-mix shotcrete should have a minimum air content of 6% before shooting. Testing of in-place air content is done in accordance with ASTM C 173 or C 231.

Dry-mix shotcrete, when tested for resistance to rapid freezing and thawing per ASTM C 666, has demonstrated

good durability, especially when air entrained. 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 mixture.

1.6.6 Absorption and volume of permeable voids—The absorption test (ASTM C 642) may be conducted on hardened shotcrete to provide an overall indication of the quality 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 damaged microstructure.

Acceptable values of permeable void volume range from 14 to 17%. Typical boiled absorption values are 6 to 9%. Results vary depending on the absorptive characteristics of the aggregate. Lightweight aggregate has high absorption. 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 good quality shotcrete. A mixture shot too dry, however, will 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 adequate compaction, resulting in high permeability and high absorption values.

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-compacting effect of shotcrete. The influence of different accelerators, however, will vary (Section 2.7.1) and should be checked with test panels before use in production.

In general, high values of permeable voids or absorption usually indicate poor quality and reduced durability of the in-place shotcrete.

1.6.7 Other properties—Permeability varies according to the mixture composition (w/cm and silica fume). Shotcrete and concrete have similar coefficients of permeability for given constituent materials and w/cm . The coefficient of thermal expansion of shotcrete is approximately that of reinforcing steel, thereby minimizing internal stress development. The density of high-quality shotcrete is usually between 139 to 149 lb/ft³ (2230 and 2390 kg/m³), similar to conventional concrete. The modulus of elasticity is between 2.4 to 5.8×10^6 psi (17 to 40 GPa), again similar to conventional concrete.

1.7—Shotcrete 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 (Fig. 1.1 and 1.2).

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



Fig. 1.2—Dry-mix shotcrete lining being installed in a large water irrigation channel in Arizona.



Fig. 1.3—Applying wet-mix shotcrete: (a) as scour protection to a spawning channel; and (b) in a swimming pool.



Fig. 1.4—Applying steel fiber-reinforced dry-mix shotcrete against a rock.

(Table 1.3) to a number of materials is sometimes an important design consideration.

Shotcrete applications can be classified under three general headings:

1. *Conventional (standard typical use)*—using portland cement, conventional aggregates, and ordinary admixtures where appropriate;
2. *Refractory (high temperatures)*—using high-temperature binders and refractory aggregates; and
3. *Special (for interface bond enhancement)*—using proprietary combinations of binder and aggregate or conventional shotcrete with special admixtures.

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

- *New structures*—roofs, thin shells, walls, prestressed tanks, buildings, reservoirs, canals, swimming pools, boats, sewers, foundation shoring, ductwork, shafts, and artificial rock (Fig. 1.3(a) and (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 (Fig. 1.4);
- *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 (Fig. 1.5(a) and (b));



Fig. 1.5—(a) Deteriorated double-box culvert showing advanced deterioration and distress before repair; and (b) concrete in culvert restored with shotcrete with natural or gun finish.

- **Strengthening and reinforcing**—to strengthen and reinforce concrete beams, columns, slabs, concrete and masonry walls, steel stacks, tanks, and pipes. Shotcrete is also used for seismic rehabilitation of shearwalls, boundary elements, beams, columns, overhead joists, and slabs, and for strengthening of existing masonry and concrete walls. Shotcrete is used in structural interiors and exteriors because of its speed and flexibility of application; and
- **Ground support**—extensively as temporary and permanent ground support. It has become the primary method of ground support in tunnels and mines (ACI/ASCE 1976; Ward and Hills 1977). It is also used extensively as lagging instead of wood for soldier pile and lagging shoring systems, and is the lagging in soil nailing.

1.7.2 Refractory shotcrete—Shotcrete applications 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. It 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 installation and “bench” shooting for thick layers has opened new fields for refractory shotcrete use.

1.7.3 Special shotcrete—Special shotcretes include proprietary mixtures for corrosion- and chemical-resistant applications. Portland cement with admixtures or other types of cements are used to produce special corrosion- and chemical-resistant properties. Special cements include magnesium phosphates cements and calcium aluminate cement. Polymer-modified shotcrete is also sometimes used. Special shotcretes find application in 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.

1.8—New developments and potential future uses

1.8.1 General—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 robot and remote control shotcrete devices, have spurred the development of ground support techniques competitive with conventional rock bolt and mesh and steel rib supports (ACI/ASCE 1974).

1.8.2 Fiber-reinforced shotcrete—The addition of steel or synthetic fibers in conventional and refractory shotcrete has been gaining favor during the past two decades. The fibers at normal addition rates can provide improved flexural and shear toughness, and impact resistance. For refractory shotcrete, stainless steel fibers increase resistance to thermal shock, temperature cycling damage, and crack development. Some specific applications where fiber-reinforced shotcrete can be cost effective are slope protection (Fig. 1.4), 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.

Synthetic fibers may reduce the susceptibility of shotcrete to plastic shrinkage cracking. At higher addition rates, they can also improve flexural toughness (ASTM C 1018). Shotcrete builds up as multiple thin layers with each succeeding layer flattening the previous layer, which causes fibers to lay roughly parallel to the surface so they are more effective than the random distribution that occurs in fiber-reinforced concrete.

Fibers may have larger rebound than normal aggregate rebound, particularly in 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 (ACI 506.1R).

1.8.3 Polymer-cement shotcrete—Adding certain polymer formulations to a conventional portland-cement shotcrete mixture improves flexural and tensile strengths, and may improve bond and reduce absorption and penetration of

chlorides. Polymer shotcrete has been used in the repair of concrete bridges and marine substructures. Polymer shotcrete has also been used in industrial plants for surfaces that are under chemical attack. The nozzle operator should exercise special care when shooting polymer shotcrete so as not to reduce bond caused by any hardened overspray and recognize the need to roughen and clean surfaces before shooting successive layers. Only a crew experienced with shooting polymer shotcrete should undertake such work. A representative of the polymer manufacturer should closely monitor the project.

1.8.4 Soil nailing—Soil nailing is a method of shoring that is used for both temporary and permanent soil retention systems. Soil nails, which are similar to tie-back anchors or rock bolts, are typically installed on a grid of 3 to 6 ft (1 to 2 m). Reinforcing mesh and reinforcing bars are then installed on the face of the soil surface, and shotcrete is applied to a nominal thickness of approximately 3 to 6 in. (75 to 150 mm). The system is installed in horizontal lifts of 3 to 6 ft (1 to 2 m) from the top down. The upper lifts of shotcrete lagging should have sufficient strength to support the face before excavating the lower lifts. The system requires a soil or rock type that will stand vertically or at the cut slope for the period of time necessary to excavate, drill and grout the nail, install the reinforcement, and install and allow the shotcrete to develop sufficient strength. In unstable soils, a stabilizing layer of shotcrete should be placed first, and then soil nails can be placed through the shotcrete layer.

1.8.5 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. Some areas of future research and development are: 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.

CHAPTER 2—MATERIALS

2.1—Introduction

Materials that produce high-quality mortar or concrete should also produce high-quality shotcrete. All materials should meet the requirements of ASTM C 1436.

2.2—Delivery, handling, and storage

All materials should be delivered to the job site in an undamaged condition. Storage of materials should be in accordance with ACI 301.

2.3—Cement

2.3.1 Portland cement—Most shotcrete is produced with Type I or I-II cements conforming to ASTM C 150 or C 595. Other cementitious materials, such as blended hydraulic cements, should meet ASTM C 1157.

2.3.2 Calcium-aluminate cement—Calcium-aluminate or high-alumina cement is a rapid-hydration cement that is used mainly for refractory applications and provides resistance to

certain acids. The use of calcium-aluminate cement should be investigated for any particular application because of its fast setting properties, high early heat of hydration, possible reduction of long-term strength by conversion, and potential differences in performance between brands. Additional information on the performance of this type of cement was reported by Neville (1980).

2.3.3 Supplementary cementitious materials—Pozzolan admixtures can be used in shotcreting. Pozzolans can enhance workability or pumpability of some wet-mix shotcrete. They may provide more resistance to sulfate attack and to alkali-silica reactivity if reactive aggregates are used. The use of pozzolanic admixtures on an equal weight replacement for cement may result in slower early strength gain. Natural pozzolans and fly ash should meet the requirements of ASTM C 618. Other pozzolans should meet the appropriate ASTM specifications. Both silica fume and metakaolin should meet the requirements of ASTM C 1240.

Ground blast-furnace slag should meet the requirements of ASTM C 989. There are three grades of slag. Generally, higher-grade slag will be finer and have greater strength development.

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 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 fume is best used in wet-mix shotcrete (Morgan 1988).

2.4—Aggregate

2.4.1 Normalweight aggregate—Normalweight aggregate for shotcrete should comply with the requirements of ASTM C 33. The combined aggregate should meet one of the gradations shown in [Table 1.1](#) of this report. Grading No. 1 should be used for fine-aggregate shotcrete and Grading No. 2 for all other shotcrete.

Aggregates failing to comply with the gradations shown in [Table 1.1](#) may be used if preconstruction testing proves satisfactory results or if acceptable service records of previous use are available.

2.4.2 Lightweight aggregates—Lightweight aggregates should conform to ASTM C 330 if used in shotcrete. The aggregate should meet one of the gradations shown in [Table 1.1](#). Wet-mix shotcrete with lightweight aggregate may be difficult to pump or shoot because the aggregate absorbs water, which reduces the plasticity of the mixture. Presaturating the lightweight aggregate before batching reduces loss of pumpability.

2.5—Water

2.5.1 Mixing water—Mixing water should be clean and free from substances that may be injurious to concrete or steel, and potable water should be used. If potable water is not available, the water should be tested to ensure that compressive strengths of mortar cubes made with it are at least 90% of that of mortar

Table 2.1—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
Other	0.3

*Adapted from ACI 318.

cubes made with distilled water (Section 3.4 of ACI 318). Cubes should be made of equal flow.

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 2.1. When testing is performed to determine water-soluble chlorine-ion content, test procedures should conform to ASTM C 1218. Also refer to the Commentary in ACI 318 for further guidance on corrosion protection of the reinforcement.

2.5.2 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 lower than 20 °F (10 °C) cooler than the shotcrete surface at the time the water and shotcrete come into contact.

2.6—Bonding compounds

Bonding compounds are generally not required nor recommended for use in shotcrete work because the bond of shotcrete to properly prepared substrates is normally excellent. If required, epoxy or latex materials are available, and the manufacturer’s instructions should be followed. Improperly used bonding compounds can act as bond breakers. Preconstruction trials should precede any extensive use of a bonding compound.

2.7—Admixtures

Admixtures may be used in shotcrete construction to enhance certain shotcrete properties for special shotcrete applications and for certain conditions of shotcrete placement. Admixtures in shotcrete should be tested before large-scale use to determine that the expected advantages can be obtained. Admixtures should meet the requirements of ASTM C 1141. Admixtures for shotcrete generally fall into the categories of accelerators, air-entrainers, water-reducers, and retarders.

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

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

- Enhance the maximum build-up thickness by increasing the early stiffness, which increases productivity by reducing the number of passes;
- Reduce the incidence of shotcrete fall-outs, thus increasing security in overhead areas; and
- 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.

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 of the long-term strength and durability. Also, the effect of a given accelerator can be cement-specific. ASTM C 1140 tests for compatibility of shotcrete accelerators and portland cement. ASTM C 1398 can determine the rate of setting and early strength development of accelerated shotcrete. Some accelerators are caustic and should be handled with care.

2.7.1.2 Rheology modifiers—Rheology modifiers are also used as accelerators in shotcrete. Examples include sodium silicate (water glass) and precipitated colloidal silica. These rheology modifiers promote a rapid stiffening of the material, therefore allowing enhanced build-up 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. Special tests, such as needle penetration tests, are available to determine the rate of setting and early strength development of accelerated shotcretes (Beaupre et al. 1993).

2.7.2 Air entrainment—Wet-mix shotcrete should be air-entrained when the shotcrete is subjected to cycles of freezing and thawing in saturated conditions. When wet-mix shotcrete is placed, however, a significant amount of entrained air is lost during shooting. Therefore, a minimum of 6% entrained air should be in the concrete mixture before shooting to compensate for the air that is lost during shooting. Some shotcreters add as much as 10% entrained air in the concrete before shooting to enhance pumpability and reduce rebound, even though the resulting in-place air content will only be 4 to 6%. Air-entraining admixtures should meet the requirements of ASTM C 260.

In general, air-entraining admixtures are not added to dry-mix shotcrete. Some shotcreters, however, have had good

results by adding air-entraining admixtures to dry-mix shotcrete to improve resistance to freezing and thawing and deicing-chemical scaling. Refer to [Section 1.6.5](#).

2.7.3 Water-reducing and retarding admixtures—Water-reducing admixtures for wet-mix shotcrete should conform to ASTM C 1141. Such admixtures are normally not used in dry-mix shotcrete. Water-reducing admixtures increase the workability of the shotcrete without increasing the w/cm .

Retarding admixtures are used when delayed set is desired, and they should conform to ASTM C 1141. 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.

2.8—Reinforcement

2.8.1 Reinforcing bars—Reinforcing bars used in shotcrete should conform to ASTM standards.

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 nozzle operator's skill becomes increasingly important to ensure complete encasement. 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 nozzle operator ([Sections 5.4.2](#) and [8.5.8](#)). Reinforcement should be free from oil, loose rust, mill scale, or other surface deposits that may affect its bond to the shotcrete.

2.8.2 Wire reinforcement—Welded-wire reinforcement should conform to ASTM A 185 or ASTM A 497 and may be uncoated or galvanized.

Commonly used fabric gages are W2 or W1.4 (4 or 3 mm) 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. Galvanized mesh can induce galvanic action when in contact with other nongalvanized steel.

2.8.3 Epoxy-coated reinforcement—Due to the abrasive nature of the shotcrete process, especially the dry-mix process, using epoxy-coated reinforcement in shotcrete applications is not recommended. If epoxy-coated reinforcement is desired, a preconstruction mockup should be shot and the effect of the shotcrete process on the epoxy coating should be examined by washing off the freshly applied shotcrete, coring, or by carefully dissecting the hardened shotcrete and examining the epoxy coating.

2.8.4 Fiber-reinforced shotcrete—Steel fibers between 1/2 and 1-1/2 in. (13 and 40 mm) long with dosage rates up to 2% by volume of the shotcrete can reduce crack propagation, increase flexural toughness, and improve ductility and

Table 2.2—Maximum volatile organic compound (VOC) limits

Coating category	lb of VOC/gal.	g of VOC/L
Concrete curing compounds (ASTM C 309)	2.9	350
Concrete curing and sealing compounds (ASTM C 1315)	5.8	700
Form-release compounds	3.8	450

impact resistance. Steel fiber dosages normally range between 34 and 118 lb/yd³ (20 and 70 kg/m³); 1% by volume requires 132 lb/yd³ (78.5 kg/m³). Steel fibers should conform to ASTM A 820.

Synthetic fibers for shotcrete are commonly polypropylene, either single filament or fibrillated, and are 1 to 2 in. (25 to 50 mm) long. Fibrillated fiber dosages of 1-1/2 to 4-1/2 lb/yd³ (1 to 3 kg/m³) are common; 1% by volume requires 15 lb/yd³ (9 kg/m³). Monofilament fibers are available and can be added at dosages of up to 2.0% volume of wet-mix shotcrete. Synthetic fibers should conform to ASTM C 1116.

2.8.5 Prestressing steel—Prestressing steel should conform to ASTM standards.

2.8.6 Other forms of steel—Other steel bars and shapes used should conform to ACI 318, Chapter 3.

2.9—Curing and form coating compounds

All form coatings and membrane-curing compounds or floor sealers should conform to the air-quality regulations applicable at the project site. Products that cannot be guaranteed by the manufacturer to conform, whether or not specified by product designation, should not be used.

The Environmental Protection Agency (EPA) has issued the National Architectural and Industrial Maintenance (AIM) Coatings Rule to regulate the volatile organic compounds (VOCs) content of AIM coatings and has issued EPA Small Entity Compliance Guide, "National Volatile Organic Compound Emission Standards for Architectural Coatings," indicating the regulations and provide guidance for compliance. Table 2.2 indicates the requirements.

CHAPTER 3—EQUIPMENT

3.1—Introduction

The successful application of shotcrete requires properly operated and maintained equipment. The contractor should choose the equipment for a project after a careful evaluation of the specifications, size, character of the work, job-site conditions, availability and quality of local materials, labor, and time available. Shotcrete equipment usually consists of, but is not limited to, a gun or pump, a compressor, a mixer, nozzles, and miscellaneous hoses. The first equipment decision involves the selection of the appropriate process: dry-mix or wet-mix.

3.2—Dry-mix equipment

Dry-mix shotcrete equipment, commonly called guns, may be divided into two distinct types: pressure vessels (batch) and rotary or continuous-feed guns.

3.2.1 Batch and double-chamber guns—Batch guns operate by placing a charge of material into the chamber and

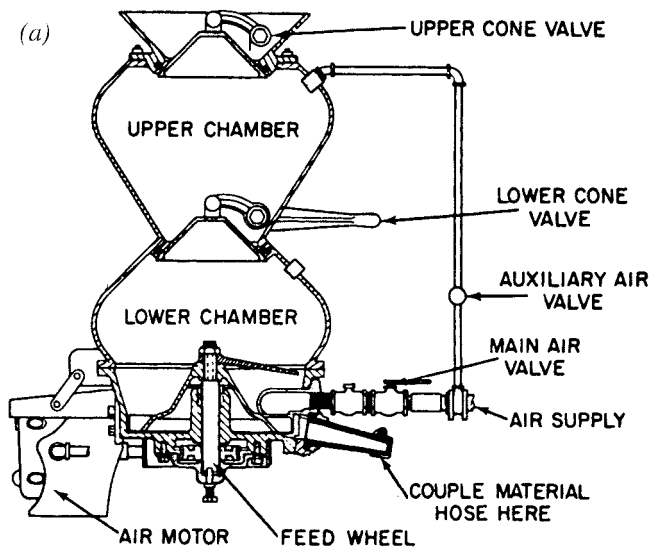


Fig. 3.1—(a) Schematic of a double-chamber gun (dry process); and (b) double-chamber gun (dry process).

then closing and pressurizing the chamber, causing the material to feed into a delivery pipe or hose.

Some single-chamber batch guns use a rotating feed wheel to give a positive metering action to the material flow.

Double chamber guns allow for continuous operation by using the upper chamber as an airlock during the charging cycle. The configuration of this type of equipment is shown in Fig. 3.1 and the operating sequence is shown in Fig. 3.2. Most double-chamber guns use a rotating feed wheel.

3.2.2 Rotary or continuous-feed guns—A rotary gun provides a continuous feeding action using a rotating airlock principle. There are two types of rotary guns: the barrel and the feed bowl. They are primarily dry-mix guns, but some types may be used for wet-mix applications.

The barrel type, as shown in Fig. 3.3(a) and (b), uses sealing plates on the top and bottom of the rotating element.

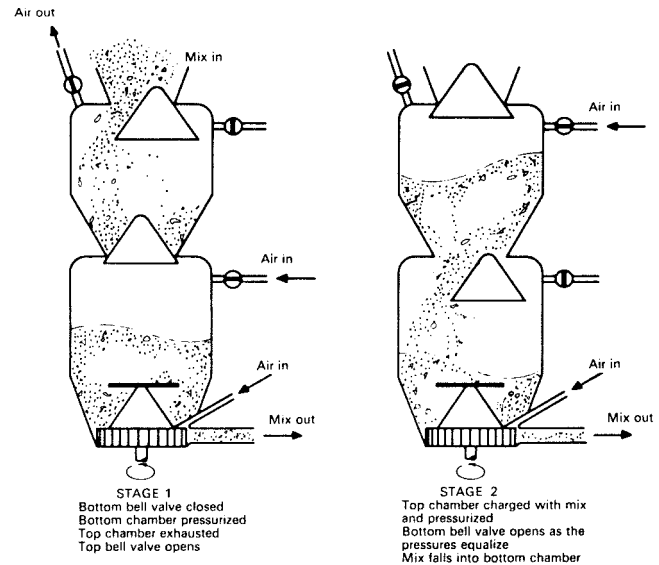


Fig. 3.2—Operating sequence of double-chamber gun.

Material is gravity-charged from the hopper into the cylinders of the rotor in one area of its rotational plane and discharged downward from these cylinders with air pressure at the opposite point in its rotation. Additional air is introduced into the outlet neck to provide proper volume and pressure for material delivery down the hose.

The feed bowl type, as shown in Fig 3.4(a) and (b), uses one sealing segment on the top surface of the rotating element.

Material is gravity-charged from the hopper into U-shaped cavities in the rotor and then discharged into the outlet neck when that particular cavity is aligned under the sealing segment. Air, which is injected down one leg of the U, carries the material into the material hose.

3.2.3 Gun safety—The gun operator should avoid cleaning the feed wheel and rotor of a gun while it is rotating. If the upper cone valve of a double-chamber gun does not seal properly, a blast of shotcrete mixture can blow into the face and eyes of the gun operator. Proper personal protective devices and preventive maintenance can reduce the effects of this hazard. To avoid accidents connected with the rotating agitator, the hopper screen of the rotary gun should be in place whenever the unit is operating. The gun operator should follow the equipment manufacturer's instructions and precautions.

The gun operator should wear goggles and a dust mask or respirator while operating the dry-mix delivery equipment. Outlet connections should be properly tightened and restrained to avoid accidents from a whipping hose and skin burn from escaping material.

Conditions at the work environment should determine the choice of air, electricity, or fuel as power for the delivery equipment.

3.3—Wet-mix equipment

A concrete pump, usually trailer-mounted, pushes the concrete mixture through the delivery hose. Early applications used a squeeze-type pump because it could maintain an almost continuous flow of concrete. A peristaltic type, or

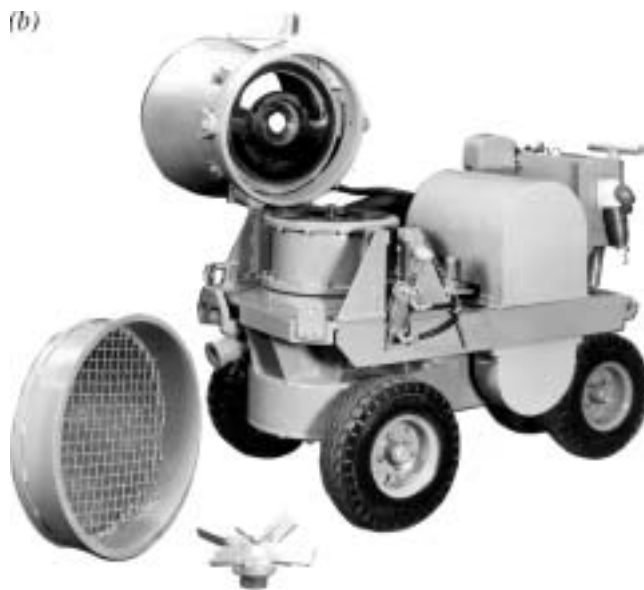
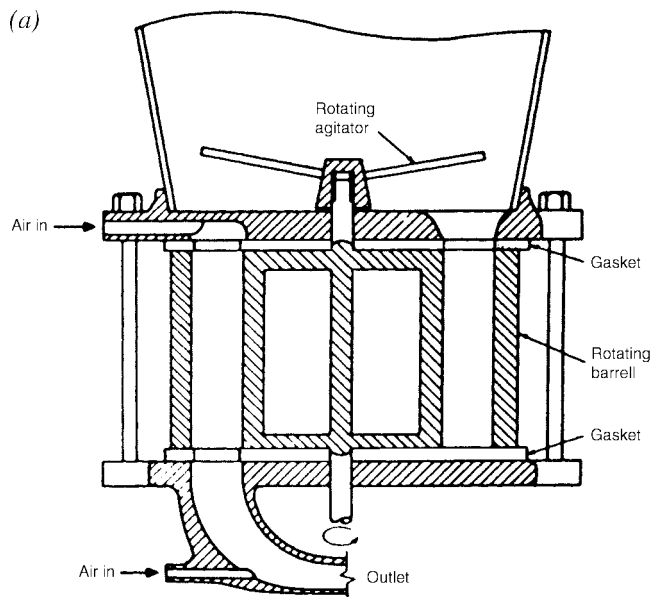


Fig. 3.3—(a) Schematic of rotary barrel gun; and (b) typical rotary barrel gun.

squeeze pump, uses mechanical rollers to squeeze the concrete through a tube into a delivery hose. Although still available, these pumps have been largely replaced by positive-displacement piston pumps with a hydraulically powered valve, as illustrated in Fig. 3.5, or a ball-check-controlled concrete flow. Positive displacement pumps are capable of much higher operating pressures than ball-check equipment. Pump pressures of 500 to 1000 psi (3.5 to 6.9 MPa) for placement rates of 8 to 16 yd³/h (6 to 12 m³/h). The diameter of the outlet housing on most shotcrete pumps is 5 in. (125 mm), although smaller pumps with 3 in. (75 mm) pistons can be used in situations requiring lower applications rates, such as low-volume repair work.

Wet-mix shotcrete equipment is used where higher production rates than those available with dry-mix equipment are advantageous. Line accumulators or surge suppressors, which use a

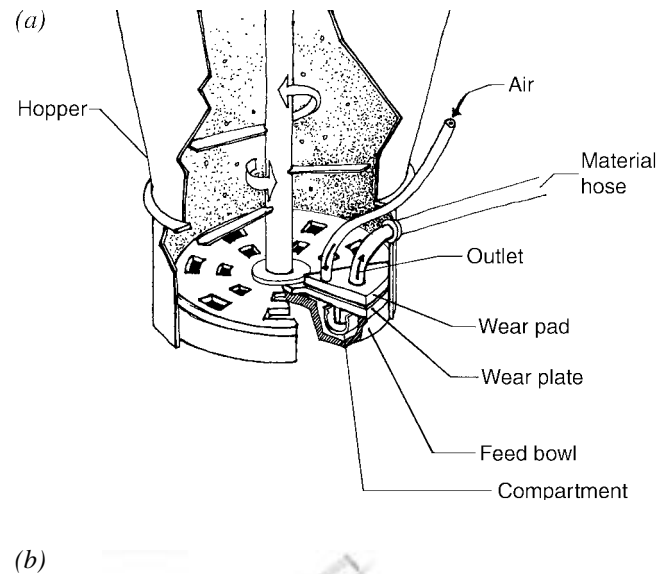


Fig. 3.4—(a) Schematic of rotary feed bowl-type gun (dry process); and (b) typical feed bowl gun (dry process).

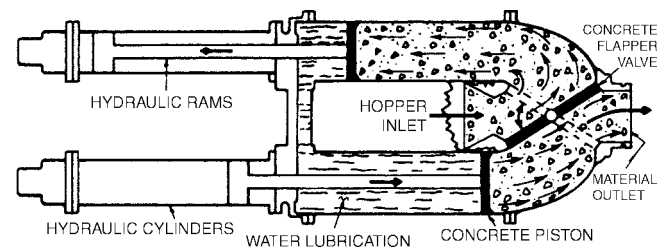


Fig. 3.5—Schematic of concrete pump.

compressible gas to absorb peak line pressures, are available and may be necessary when shotcreting at high volumes.

The gun operator should explicitly follow the manufacturer's recommendations for the safe operation and cleaning of wet-process equipment. The precautions listed in [Section 3.2.3](#) also apply to the wet-mix process.

Table 3.1—Compressor capacities and hose diameters

Material hose inside diameter, in. (mm)	Compressor capacity	
	ft ³ /min at 100 psi	m ³ /min at 0.7 MPa
1 (25)	350	10.0
1-1/4 (32)	450	12.5
1-1/2 (38)	600	17.0
2 (51)	750	21.0
2-1/2 (64)	1000	28.0

3.4—Air requirements

3.4.1 Dry-mix—A properly operating air compressor of extra capacity is essential to a satisfactory shotcreting operation. The compressor should maintain a supply of clean, dry, oil-free air adequate for maintaining required nozzle velocities while simultaneously operating all air-driven equipment and a blow pipe for clearing away rebound. Operation of compressors at higher elevations requires increased volumes of air. Compressed air requirements vary depending on the type of equipment, its condition, and the mode of operation. It is advisable to check the gun manufacturer's recommendations for required compressor capacity.

The compressor capacities shown in Table 3.1 are a general guide for shotcrete applications using air-motor-driven dry-process guns.

These air capacities should be adjusted for compressor age, altitude, hose and gun leaks, and other factors that reduce the rated capacity of the air compressor. In addition, hose length, unit weight of material, bends and kinks in the hose, height of the nozzle above the gun, and other air demands will affect the air requirements of a particular equipment layout.

The operating air pressure drives the material from the gun into the hose and is measured at the material outlet or air inlet on the gun. The operating pressure varies directly with the hose length, the density of the material mixture, the height of the nozzle above the gun, and the number of hose bends. Operating pressures should not be less than 60 psi (0.4 MPa) when 100 ft (30 m) or less of material hose is used, and the pressure should be increased 5 psi (0.03 MPa) for each additional 50 ft (15 m) of hose and 5 psi (35 kPa) for each additional 25 ft (8 m) the nozzle is above the gun.

3.4.2 Wet-mix—The wet-mix concrete pump provides the energy to move the shotcrete material to the placement area. Air, however, is needed to increase the velocity of the material as it exits the nozzle. A smaller compressor is appropriate for wet-mix shotcreting. For wet-mix, 200 to 350 ft³/min (5.6 to 10 m³/min) air volume at 100 psi (0.7 MPa) is needed. Higher capacities are needed for higher volume and higher-velocity shotcreting.

3.5—Mixing equipment

3.5.1 Dry-mix—Dry-mix applications can use mixtures that are mixed on site, supplied in dry-bags, or delivered to the job site in concrete trucks.

Mixing equipment for dry-mix shotcrete work falls into two general categories: batch and continuous. Both are available

in a range of types and sizes from different manufacturers. The batch type uses a drum mixer with fixed integral blades or a rotating paddle with or without an elevating conveyor. The continuous type uses a trough with a screw or auger that mixes and elevates the material at the same time.

The equipment for proportioning mixtures varies from the simple volumetrically calibrated box to highly sophisticated electronic devices.

Proportioning for continuous mixing can be accomplished by equipment designed with separate aggregate and cement hoppers. Individual ingredients are fed to a mixer screw by variable-speed augers, or belt-feed systems, or a combination of both. This equipment should conform with ASTM C 685. The selection of a specific mixing and proportioning technique depends on the nature of materials specified, production requirements, the type of delivery equipment (gun) used, and size and type of shotcrete application.

The equipment should be capable of batching and mixing the specified materials in sufficient quantity to maintain continuous placement. Satisfactory evidence should be presented that the mixer is capable of thoroughly mixing and supplying a homogeneous and consistent mixture. The mixer should be capable of discharging all mixed material to prevent buildup or accumulations of hydrated and caked materials in the mixing bowl and conveyor. The mixer should be thoroughly cleaned as necessary and at least once daily at the conclusion of work.

A hopper is sometimes used in high-production units of both of these types to collect and feed the mixture as required. Water-metering systems are also available to predampen the mixture.

Equipment of this type is also available for dry-mix or wet-mix shotcrete applications using fine aggregate or a coarse-and-fine aggregate combination.

3.5.2 Wet-mix—Concrete trucks usually supply concrete for wet-mix shotcreting. Volumetric-measuring and continuous-mixing concrete equipment covered by ACI 304.6R and conforming to ASTM C 685 also may be used to supply material for wet-mix shotcreting. Continuous auger mixers are well-suited for wet-mix. The auger mixers eliminate waste and provide freshly mixed material.

3.6—Hoses

The selection of the proper material delivery, air, and water hoses is important for proper equipment operation, economy, and safety. Hose size and operating pressures should be analyzed and evaluated when selecting the appropriate hose. Hose couplings should not obstruct flow and should have proper safety restraints for blowout protection and be quick acting. Dry-mix equipment usually uses threaded and half-turn connectors.

3.6.1 Air hose—An air hose supplies air to the shotcrete gun, the nozzle in the wet-mix process, the blow pipe, and other air-operated equipment and tools. The air hose should be large enough to ensure a proper volume of air to operate the equipment. Air hoses should be capable of withstanding at least twice the operating pressure; have an oil-resistant

tube and cover; be light, flexible, and noncollapsible; and resist kinking and abrasion.

For the dry-mix process, the inside diameter of the air supply hose from the compressor to the gun should be at least as large as the inside diameter of the material hose. For the positive displacement wet-process equipment, the air hose to the nozzle is 3/4 in. (19 mm) or 1 in. (25 mm) inside diameter, equipped with half-turn couplers.

3.6.2 Water hose—A water hose is used for supplying water to the booster pump, mixer, and nozzle. The water hose should be of a size and strength compatible with the required rate of flow and pressure. Some applicators use an air hose similar to that described in [Section 3.6.1](#). A minimum inside diameter of 3/4 in. (19 mm) is recommended for all water hoses.

3.6.3 Material hose—Material delivery hoses are available in several different constructions for both dry- and wet-process shotcrete applications. The internal hose diameter should be three times the size of the largest aggregate particle in the mixture. Material hose diameters for steel fiber-reinforced shotcrete should be a minimum of one-and-a-half times the fiber length; for synthetic fibers, the multiple should be at least one.

3.6.3.1 Dry-mix—In general, the material delivery hose should be lightweight and flexible, have an abrasion-resistant tube and cover, be noncollapsible, and resist kinking. Shotcrete mixtures containing coarse aggregate are much more abrasive than those containing fine aggregate only, which increases hose wear. Hoses with tubes of special, tough rubber should be used in this case.

Maintenance, screening the material, maintaining proper moisture content, and properly proportioning the mixture for the equipment and materials available can reduce plugging. In the dry-mix process, material with a low moisture content can create static electricity buildup while passing through the hose, which can shock the nozzle operator and cause a loss of control of the nozzle. To prevent this problem, the nozzle operator should ground the gun, using a special antistatic hose, and maintain the proper predampening moisture in the aggregate.

3.6.3.2 Wet-mix—Concrete transported to the shotcreting area by pumping methods is pumped through flexible material hose or rigid steel tubing, both of which are called pipeline. Refer to ACI 304.2R for more details.

The internal diameter of the material hose is normally 2 or 2-1/2 in. (50 to 63 mm). This hose is reinforced with multiple plies of synthetic cord or steel wire. The inner liner is manufactured with wear-resistant natural rubbers, and the outer cover provides ozone and wear protection.

All hose ends should be the heavy-duty types with a raised shoulder. They are joined by two-piece coupling devices that incorporate a sealing gasket and are closed with an adjustable snap or two-bolt coupler.

Steel tubing 10 ft (3 m) long and 3 to 5 in. (75 to 125 mm) in diameter is frequently used in wet-mix shotcrete applications. The sections of pipeline have the same type ends and use the same type couplers as the flexible material hose. Steel pipelines have less internal friction so the amount of force required to pump through a steel line is about 1/3 that

required of a flexible line. Steel lines also reduce surge and cost less.

To reduce pump pressures, use steel pipe and limit the length of flexible hose if possible.

Flexible hose is used at the end of the pipeline to provide access to the entire placing area. When the concrete pump must be located further from the placement area, a steel pipeline or larger-diameter hose should be used. Long-tapered reducers are used to join components of different diameters.

3.6.4 Hose safety—All hoses (water, air, and material) are subject to rupture and coupling breaks. To minimize these risks, the shotcreter should use a hose capable of withstanding pressures of twice the working pressure. In addition, safety chains or cables should be installed on all couplings to minimize hose whip should the coupling fail. Material hose plugging can cause coupling breaks or hose rupture during operation, with the possibility of hose whip, skin burn, or both. Dry-mix material hoses become plugged when oversized particles or objects find their way into the mixture, the hose diameter is reduced in section by material caking (wet aggregate), the volume of air is insufficient to move the material in the hose, or a poor aggregate gradation is used.

Cleaning or unplugging the hose using air pressure is hazardous unless the ends of the hose are adequately restrained. High pressures can cause severe hose and nozzle whipping as a plug exits. Couplings should never be opened until it is confirmed that line pressure has been relieved.

Uneven wear of the hose wall, especially on the outer side of a curved or looped hose, can rupture a material hose. Hoses should be used in straight lengths, if possible, and supported when hung vertically. Failure at the coupling in material hoses is a frequent source of trouble. Couplings should be inspected frequently because a break in a heavy metal coupling can pose a potential hazard.

3.7—Nozzles

Discharge nozzles consisting of a nozzle body and nozzle tip are attached to the end of the material delivery hose to inject water or air into the moving stream of materials. The nozzle also permits the addition of premixed water and solids and provides uniform distribution of the mixture. Ideally, dry-mix nozzles should pattern the discharge as a uniform inner cone consisting primarily of solids and some water spray surrounded by a thin outer cone, which is mainly water spray. The nozzle tip size should not exceed the diameter of the hose and often is smaller.

3.7.1 Dry-mix—The dry-mix nozzle consists of a nozzle tip, water ring, control valve, and water body, as shown in [Fig. 3.6](#). The tip can be made of rubber, elastomer material, or metal with a rubber liner. They vary in length and may be straight, tapered, rifled, single or double venturi, or 90 degrees.

Figure 3.7 illustrates a hydromix nozzle, which has a nozzle body that is separate from the nozzle tip by a 12 to 36 in. (300 to 900 mm) section of delivery hose.

This configuration allows for longer premixing of solids and water, reduces rebound and dust, and increases homogeneity. It is particularly helpful if the aggregate moisture

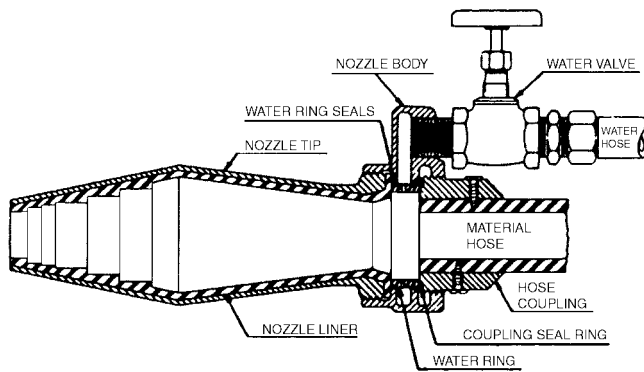


Fig. 3.6—Dry-mix nozzle.



Fig. 3.7—Hydromix nozzle.



Fig. 3.8—Prewetting long nozzle.

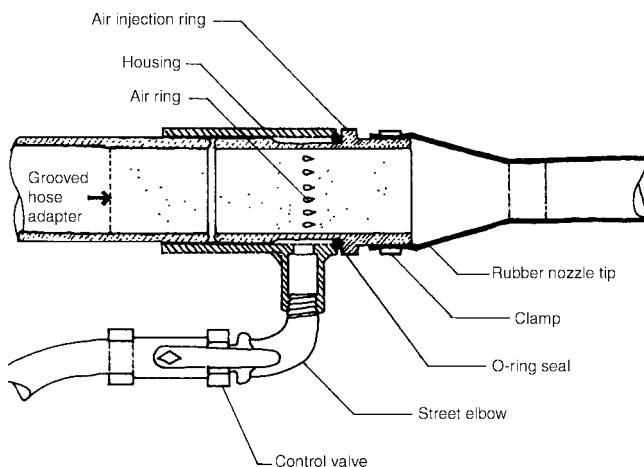


Fig. 3.9—Wet-mix nozzle.

is less than optimum. An extended hydromix nozzle is shown in Fig. 3.8.

With a hydromix nozzle, the material is prewetted 10 to 20 ft (3 to 7 m) before reaching the nozzle, where additional water is injected. Some tests show improved physical properties of the shotcrete when installed using the long nozzle. Some shotcreters have experienced increased yield due to a much lower rebound loss factor. Nozzle operators accustomed to a standard nozzle may find that a long nozzle with the extra hose is harder to handle than a standard nozzle.

3.7.2 Wet-mix—In wet-mix, compressed air is injected in the nozzle to increase the exit velocity of the mixture. A typical wet-mix nozzle (Fig. 3.9) consists of a rubber or special plastic nozzle tip, an air injection ring, a control valve, and the housing. Once the concrete enters the pump, the w/cm is not altered. Accelerators may be added at the nozzle.

3.8—Auxiliary equipment

The equipment described to this point is the minimum required to apply shotcrete. There is, however, a considerable body of auxiliary equipment frequently required to ensure economical, high-quality shotcrete. A particular device may facilitate placement procedures, overcome the rigors of climate or temperature, compensate for material inadequacies, provide a safe working environment, or alter the properties of the final product. Included among this equipment are water booster pumps and heaters, scaffolding, air movers, communication devices, space heaters, light plants, blow-pipes, aggregate dryers, fiber feeders, and admixture dispensers.

3.8.1 Water booster pumps—In dry-mix applications, a pressure-boosting device is needed when available pressure is inadequate to properly wet the mixture. A minimum pressure of 60 psi (0.4 MPa) should be available at the nozzle, but this pressure should always be substantially greater than the operating air pressure (Section 3.4.1). High-pressure booster pumps with surge tanks to provide uniform flow are used for this purpose.

3.8.2 Water heaters—For cold-weather dry-mix shotcreting, a water heater may be required to bring the temperature of the mixture above 60 °F (16 °C). Ideally, the water heater should have regulated temperature control, safety devices, and enough capacity to heat the required water flow.

3.8.3 Scaffolding—Working platforms should be stable. This can be provided with tubular frames, wood scaffolds, personnel lifts, and fixed swinging stages. The working platform should meet all applicable safety standards and not interfere with nozzle operation.

3.8.4 Air movers—In confined and closed areas, dust and vapor from the dry-mix shotcrete operations can cloud the area in a few minutes. Visibility may be reduced to almost zero, preventing the nozzle operator from having a clear view of the work. Adequate ventilation in the form of blowers, fans, and venturi air-movers will help to alleviate the problem.

3.8.5 Communication devices—The nozzle operator and gun or pump operator should be in constant and clear contact throughout the placement operation. When line-of-sight signals are impossible, communication should be maintained through the use of sound-powered or electric telephones, radios, low-voltage bells, or an air whistle.

3.8.6 Space heaters—To ensure proper and complete hydration of the freshly placed shotcrete, the shotcrete should be cured at temperatures specified in ACI 306R. Space heaters that provide vented heated air, or infrared heaters, are recommended. Fuel-burning heaters should be vented to prevent carbonation of the shotcrete.

3.8.7 Lighting—Because dust and mist affect visibility in confined areas, some type of floodlighting is usually necessary.

The system should be watertight and reflectors should have lens guards to prevent shattering the lamps.

3.8.8 Blowpipes—A blowpipe is used to help keep rebound, overspray, and loose debris from the advancing work. The blowpipe is usually fabricated from 1/2 or 3/4 in. (13 or 19 mm) diameter pipe approximately 4 ft (1.2 m) long and equipped with a control valve and tapered or flattened exhaust tip that directs air to blow away rebound or overspray (Fig. 3.10).

3.8.9 Aggregate dryers—Occasionally, the aggregate needs to be dried or heated before use in the shotcrete mixture. In that situation, the shotcreter should place corrugated metal pipe under the aggregate pile and introduce heat or hot air into the pipe or pass the aggregate through a rotary kiln-type dryer. Depending on air temperature, cooling the aggregate before use may be necessary.

3.8.10 Fiber feeders—Fibers in shotcrete should be uniformly distributed throughout the mixture. This may be difficult to achieve because loose, high-aspect-ratio steel fibers tend to clump or ball. Normally, batch proportioning and the use of appropriate screens can prevent this problem. Continuous proportioning equipment may also be used, provided the feeder is carefully synchronized with the mixer. Using loose, low-aspect-ratio fibers or collated fibers that artificially reduce the aspect ratio reduces balling problems.

3.8.11 Admixture dispensers—Job conditions may dictate the use of an admixture in shotcrete. Admixtures are available as dry powder, liquid, or both. They may be added during mixing or at the nozzle, depending on their properties, the type of shotcrete process (dry or wet) (Fig. 3.11), and whether the placement will be adversely affected. ASTM C 1141 provides information on using admixtures for shotcrete.

3.8.11.1 Dry-mix—In the dry-mix process, dry (powder) admixtures are usually introduced into the mixture at the batching stage. If a continuous feed gun is used, a special dispenser may also add admixtures directly into the gun hopper. When prebagged material is used, powdered admixtures should be mixed with the dry ingredients during packaging.

In the dry-mix process, the shotcreter should introduce liquid admixtures to the mixture at the nozzle and in combination with the mixing water. The admixture may be premixed with water and pumped to the nozzle or added directly to the mixing water at the nozzle.

3.8.11.2 Wet-mix—In the wet-mix process, dry or liquid admixtures may be added to the mixture at the batching and mixing stage, provided the pumping properties are not significantly adversely altered. This includes air-entraining, water-reducing, mid-range, and high-range water-reducing (HRWR) admixtures. When HRWR admixture is used, the shotcreter should complete shotcreting before the consistency (plasticity) of the mixture significantly degrades. In addition, admixtures may be added to the air supply at the nozzle as shown in Fig. 3.11, providing they are proportioned to the delivery rate of the mixture through the material hose.

3.8.12 Predampener—A predampener is a device usually comprised of an auger and water spray bar that is used to predampen dry-mix shotcrete materials (typically to a 4 to

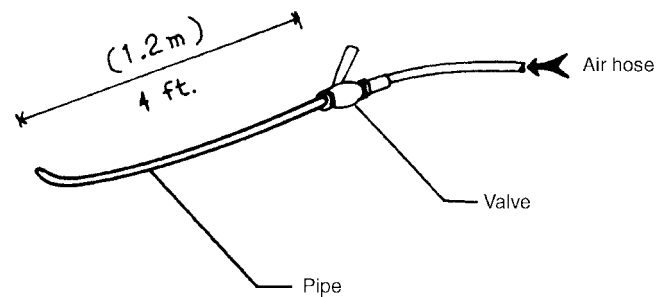


Fig. 3.10—Air blowpipe.

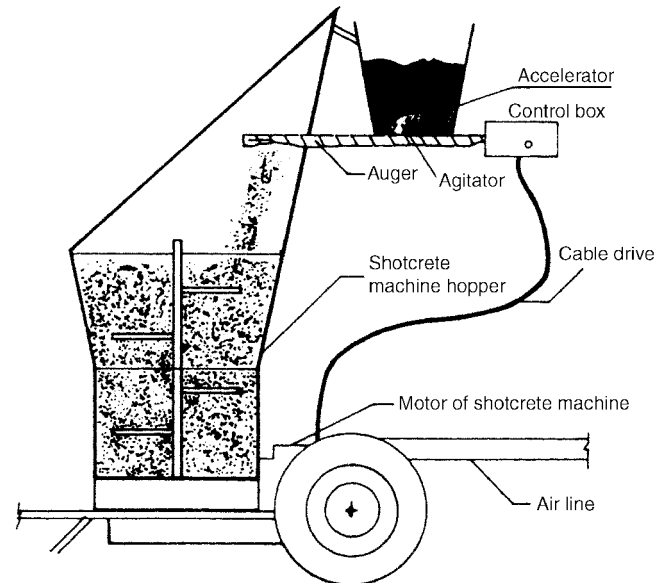


Fig. 3.11—Wet-mix system that adds accelerator.

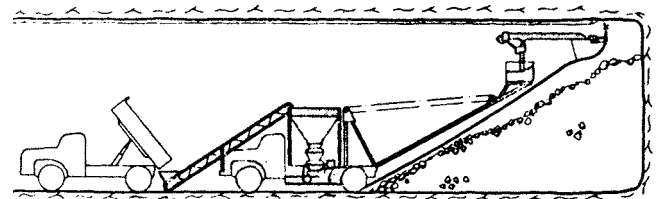


Fig. 3.12—Remote nozzle boom.

6% by mass moisture content) before they are discharged into the shotcrete gun.

3.8.13 Remote shotcrete equipment—Shotcrete is widely accepted and used for excavation and underground support. With this acceptance has come the development of highly sophisticated equipment using remote-controlled and semiautomatic nozzle booms. The operator is set safely back from the face of excavation out of the range of rock falls. The boom has complete freedom of movement in all directions, even to the extent of quickly moving the nozzle back and forth across the rock surface. Figure 3.12 shows a typical arrangement.

3.9—Plant layout and operation

3.9.1 Plant layout—Proper plant layout is essential for efficient, economical, and successful shotcrete operation.

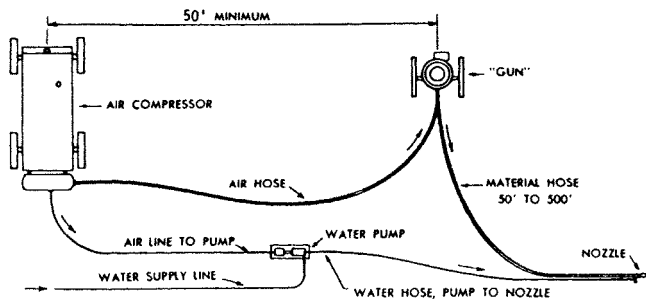


Fig. 3.13—Typical arrangement (plan view) of equipment for dry-mix shotcreting.

The equipment should be placed as close to the work as possible to minimize the length of the material hose required. If the work is spread over a considerable area, the plant should be centrally located to reduce the number of equipment moves required to complete the project. To avoid duplicate material handling, the plant should be positioned so that material suppliers have easy and direct access to the mixer or pump. A typical plant layout is illustrated in Fig. 3.13.

3.9.2 Plant operation—Properly maintained equipment is a key requirement for producing high-quality shotcrete on a regular basis. Inspecting and cleaning each piece of equipment at least on a daily basis is imperative. Equipment should be greased, oiled, and generally maintained on a regular schedule. A preventive maintenance program should be established. Meetings should be held regularly to teach operators on the proper use and maintenance of their equipment. Adequate backup equipment and spare parts should be readily available to minimize downtime.

3.10—Other uses of shotcrete equipment

3.10.1 Sandblasting—Dry-mix shotcrete guns may be used as a sandblasting tank for light sandblasting. They are not as efficient or effective as standard sandblasting equipment; however, these guns avoid the need to have a duplicate set of equipment and material on hand and will do a satisfactory job for many applications.

3.10.2 Pressure grouting—Some dry-mix and wet-mix shotcrete machines are adaptable to certain types of pressure grouting. The type of application determines the feasibility of using a particular unit.

3.10.3 Backfilling—Dry-mix shotcrete machines may be used to install fine aggregates or other fillers as backfill in distant, inaccessible, or restricted locations. Some uses include filling the annular space between concentric pipelines, filling abandoned pipelines and tanks, and filling the space behind prefabricated tunnel liners before grouting.

3.11—Safety

The shotcrete crew should wear goggles, dust masks, or respirators. The crew should wear long-sleeve shirts to protect against cement burns. All guards and screens should be in place whenever any equipment is operating. The operator should relieve air pressure before opening any chamber or hose, and relieve pump pressure before opening the material line or pipeline. The operator should follow the manufacturer's

operational recommendations and safety precautions. The crew should not insert shovels, bars, rakes, or other objects near or in moving parts of mixers.

CHAPTER 4—CREW ORGANIZATION

4.1—Introduction

The shotcreting crew, consisting of competent supervisors and skilled craftsmen, should be trained, integrated, and motivated to provide a team effort that results in a shotcrete application of the highest quality possible. This chapter describes a typical shotcrete crew, its duties, and some methods of communication used during shotcreting.

4.2—Composition and duties

The basic shotcrete crew may consist of a foreman, a nozzle operator, a finisher or rodman, an assistant nozzle operator, a gun or pump operator, a mixer operator, and laborers.

Some duties may be combined by having one person perform more than one operation. For example, the foreman could also function as the nozzle operator; one person could perform the finisher or rodman and assistant nozzle operator tasks; or the gun or pump operator and mixer functions could be combined and one person could perform the tasks. Other jobs may require more than one nozzle operator and finisher or rodman. Where several crews are operating, a superintendent, engineer, or both, may be required.

The foreman directs and coordinates the work of each member of the shotcrete crew to obtain a successful application.

4.2.1 Foreman's duties—The foreman plans and organizes the crew and work, and monitors quality-control procedures. The foreman is responsible for the inspection and maintenance of equipment and ordering and expediting delivery of materials. The foreman sets the pace of the work, maintains crew moral, ensures good housekeeping, and acts as liaison to either the general supervisor or to the owner's inspection team. The foreman is usually a veteran nozzle operator, finisher or rodman, and gun/pump operator, and should be able to fill any of the positions if required.

4.2.2 Nozzle operator's duties—The nozzle operator is a key person in a shotcreting operation and is responsible for applying the shotcrete and for bringing it to required line and grade in a workman-like manner. The nozzle operator's duties include coordinating the application with the foreman, finisher or rodman, and gun/pump operator. Before shotcreting, the nozzle operator should see that all surfaces to be shot are clean, sound, and free of loose material, and that anchors, reinforcement, and ground wires are properly placed and spaced. During shotcreting, the nozzle operator controls the water content for dry mixtures and ensures that the operating air pressure is uniform and will provide high velocity at impact for good compaction. The nozzle operator provides leadership and direction for the shotcrete crew, which aids in the task of shooting high-quality shotcrete. The nozzle operator is usually an accomplished finisher or rodman and gun/pump operator.

4.2.3 Finisher or rodman's duties—The finisher or rodman trims and scrapes the shotcrete, bringing it to line and grade before final finishing. The finisher or rodman also

locates and removes sand pockets, over-dry areas, sags, and sloughs, and guides the nozzle operator to low spots that require filling with shotcrete. After the shotcrete sets, the finisher or rodman brooms or prepares the surface for future application. Some applicators combine the duties of finisher or rodman and assistant nozzle operator on small projects.

4.2.4 Assistant nozzle operator's duties (blowpipe operator)—The assistant nozzle operator (nozzle operator helper) helps the nozzle operator by dragging the hose and performing other duties as directed by the nozzle operator. The assistant nozzle operator relays signals between the gun/pump operator and nozzle operator and may also relieve the nozzle operator for short rest periods. The assistant nozzle operator operates the blowpipe, if one is required, to keep the areas in advance of the shotcrete free of dust and rebound. The assistant nozzle operator may be an apprentice nozzle operator.

4.2.5 Gun operator's duties—The gun operator provides a constant flow of properly mixed dry-mix material to the nozzle operator. The gun operator operates and maintains a clean shotcrete machine and assists in ensuring quality control. The gun operator should be particularly attentive to the needs of the nozzle operator and ensure that the mixture is properly prepared. The gun operator generally oversees, controls, and coordinates the material mixing and delivery operation.

4.2.6 Pump operator's duties—The pump operator regulates the pump to uniformly deliver the wet-mix shotcrete at the required rate. The pump operator is responsible for cleaning and maintaining the material hose and pump. The pump operator coordinates the delivery of concrete and monitors the water content by observing or testing the slump of the mixture.

4.2.7 Mixer operator's duties—The mixer operator's duties include, where applicable, the proportioning and mixing of the material, and maintaining and cleaning the mixing equipment. For field mixing, the mixer operator is responsible for storage, care, and accessibility of the materials. The mixer operator sees that the mixture is free of extraneous materials and lumps and that the aggregates have the proper moisture content. The mixer operator ensures a constant flow of shotcrete but is also careful not to mix more material than can be used within the specified time limits. The mixer operator supervises the laborers who are supplying and loading the mixer.

4.2.8 Laborer's duties—The laborer's duties include moving equipment, hoses, scaffolding, and materials. Laborers clean work areas, remove rebound and overspray, and provide support for the shotcrete application.

4.2.9 Shotcrete engineer or superintendent—On large or complicated projects, a shotcrete engineer or superintendent may be advisable. A shotcrete contractor usually employs engineers, superintendents, or both, but they may not be assigned full-time to a single project. The shotcrete engineer or superintendent is responsible for the material selection, mixture proportioning, preconstruction testing, qualifications of the crew, equipment selection, project planning, scheduling, logistics, materials handling, quality control, sampling and testing coordinating, and troubleshooting technical problems

during construction. The shotcrete engineer or superintendent should have at least one year of relevant field experience.

4.3—Crew qualifications

4.3.1 General—The quality of a completed shotcrete application results from the combined skills and knowledge of the shotcrete crew. The foreman and crew should have performed satisfactory work in similar capacities for a specified period.

4.3.2 Foreman—The foreman normally has proficiency at all crew positions and is in charge of the crew. The foreman typically has at least one year of experience on shotcrete projects.

4.3.3 Nozzle operator—The nozzle operator should be certified (refer to ACI CP-60) and have completed at least one similar application as a nozzle operator on a similar project. The nozzle operator should also be able to demonstrate, by test, an ability to satisfactorily perform the required duties and to apply shotcrete as required by specifications.

4.3.4 Finisher or rodman—The finisher or rodman should have shotcreting experience; however, if his/her previous work experience provided acceptable results, this should qualify the finisher or rodman for the position.

4.3.5 Gun or pump operator—The gun or pump operator should be familiar with and be able to operate the shotcrete delivery equipment, know the proper methods of material preparation and mixing, and be familiar with the communication method in use. Preferably, the pump operator should have at least one year of experience as a gun or pump operator.

4.4—Communications

Communication plays a vital role during the shotcreting application. Because of many factors, such as the distance between the nozzle operator and gun or pump operator, objects obstructing their view of each other, and noise levels that prevent oral communication, the shotcrete crew should select an appropriate communication system.

4.4.1 Communication methods—Several methods of communications are used within the industry. A practical method is hand signals. With this method, the nozzle operator or assistant nozzle operator holds up one or two fingers in view of the gun or pump operator, indicating that the operator should regulate either the air pressure or material feed, respectively. Other signals may be used by individual companies and are normally customized to individual preference. Hand or other methods of communications, such as whistles, two-way radios, or voice-activated telephone, may also be used. Normal communication during shotcreting requires signals for raising and lowering the air pressure, starting, speeding up or slowing down the motor, and most important, a provision for shutting down the equipment in the event of a blockage or dangerous surge in pressure. Whatever method is selected, each crew member should understand the signals to ensure a safe and proper application ([Section 3.8.5](#)).

CHAPTER 5—PRELIMINARY PROCEDURES

5.1—Introduction

The quality of a shotcrete application is dependent on the care taken in the preparation and maintenance of the surface before and during shotcrete application. All shotcrete must be placed against some type of surface, and satisfactory results can only be obtained if proper attention is given to the condition and integrity of the receiving surface.

5.2—Surface preparation

The amount of surface preparation required depends on the condition and nature of the surface against which shotcrete is to be placed and the desired end product. If the receiving surface is only a form and bond is not important, little, if any, preparation is needed. Because the shotcrete impact will cause loose material from the substrate to combine with the shotcrete, the first few inches of the in-place shotcrete will have loose material mixed into the in-place shotcrete. The following sections discuss special requirements of surface preparation for earth, steel, concrete, masonry, rock, and wood surfaces.

5.2.1 Earth surfaces—The range of shotcrete applications covering earth surfaces is extremely broad and includes swimming pools, slope protection, canal linings, open channels, reservoirs, and holding basins. Proper preparation and compaction of the earth is essential. The earth surface is then trimmed to line and grade to provide adequate support and to aid in obtaining the designed thickness of the shotcrete. The shotcreter should not place shotcrete on an earth surface that is frozen or spongy. To prevent excessive absorption of mixing water from the shotcrete, the following techniques are available:

- Prewet the earth surface by spraying water before applying the shotcrete. The amount of predampening will depend on the absorption qualities of the earth; however, puddling, ponding, or leaving freestanding water should be avoided; and
- A moisture barrier system may be installed that will inhibit the movement of moisture from the newly placed shotcrete into the earth. If sheet material is used, care should be taken to avoid wrinkling or folding to eliminate the formation of voids beneath the moisture barrier or creation of a thin layer of shotcrete.

To prevent wash-out of freshly placed shotcrete due to water seepage, the seepage should be controlled using conduits to channel the water. After water seepage is controlled, the shotcrete can then be placed and when the shotcrete has set, the water conduits can be hand-plugged using flash-setting cement.

5.2.2 Steel surfaces—Before shotcrete is applied over steel surfaces, all unacceptable amounts (to be judged by designer) of loose mill scale, rust, oil, paint, or other contaminants as described below should be removed by sandblasting or other methods. Refer to ACI 546R, SSPC-SP13/NACE No. 6 and ICRI Technical Guideline No. 03737, “Guide for the Preparation of Concrete Surfaces for Repair Using Hydrodemolition Methods.”

If high-pressure water blasting is used, all freestanding water should be removed before applying shotcrete.

5.2.3 Concrete surfaces—It is imperative to completely remove all spalled, severely cracked, deteriorated, loose, and unsound concrete from the existing concrete surface by chipping, scarifying, sandblasting, water blasting, or other suitable mechanical methods. Refer to SSPC-SP13/NACE No. 6 for more information. Any concrete that is contaminated by chemicals or oils should be removed. Abrupt changes in the repair thickness should be avoided. The perimeter of the repair may be saw-cut to a depth compatible with the depth and type of repair. Edges that are chipped should taper at approximately 45 degrees toward the center of the repair area. Feather edging should be avoided.

If pneumatic or electric impact tools are used for removing the concrete, the tools should be chosen to minimize damage to sound concrete that may underlie or abut deteriorated material. Where shotcrete is to be placed against a smooth concrete surface, the surface should be roughened by sandblasting, bush hammering, or by other suitable mechanical means.

Following initial removal, the surface of the existing concrete should be inspected to see that only sound material remains. This is particularly critical if mechanical impact removal, such as bush hammering, has been used because there is a possibility of residual fractured fragments on the surface. Sounding with a hammer has long been used as a method of inspection to check for delaminations and hollows; however, this method may only be capable of detecting them within 4 to 6 in. (100 to 150 mm) of the surface.

When surface preparation is completed, all repair areas should be thoroughly cleaned by sandblasting, hydromilling, or other methods to remove any traces of dirt, grease, fractured concrete, oil, or other substances that could interfere with the bond of the newly placed shotcrete. If sandblasting is used, the excess sand and loose debris should be vacuumed or blown from the surface with compressed air, water, or both. Particular care should be taken to remove such debris around anchors or reinforcing rods.

Adequate prewetting of the concrete substrate should be done before shotcreting. Concrete substrates should be in a saturated surface-dry (SSD) condition immediately before shotcrete application for maximum adhesion.

5.2.4 Masonry surfaces—Masonry surfaces require preparation similar to that of concrete surfaces; however, preventing absorption of water from the shotcrete into the underlying masonry is critical. Severe cracking of the shotcrete can result if this is not done. One method used to prevent this problem is dampening the masonry surface before applying shotcrete.

5.2.5 Rock surfaces—Loose material, debris, chips, mud, dirt, or other foreign matter should be removed to ensure a strong bond between the rock and the shotcrete, if desired. There may be situations, however, where complete removal may be hazardous or inadvisable, such as in some underground applications where early support is required.

5.2.6 Wood forms—If forms are to be removed after use, a form-release agent should be applied to the form to prevent absorption of moisture and to inhibit bond between shotcrete and the form. Shotcreting against a form with a form-release agent may cause the agent to mix with the shotcrete. Consequently, the type of form-release agent

should be carefully selected so as not to damage the surface skin of shotcrete. Otherwise, form requirements are similar to conventional concrete.

5.3—Formwork

Forms may be of any rigid material, such as wood, steel, paper-backed reinforcing mesh, expanded metal lath or stable inflatable form (Fig. 5.1).

In all cases, the form should be adequately braced and secured to prevent excessive vibration or deflection during the placement of the shotcrete. All formwork should be designed to provide for the escape of compressed air and rebound during shotcreting. For column construction, two sides can be formed or the four corners can be formed using light narrow wood lath; satisfactory results may be obtained where three sides are formed, provided the width is at least two times the depth. Similarly, in beam construction, the soffit and one side may be formed, leaving the other sides open, or a light lath strip can be used to delineate the soffit corners. It should be braced or shored so that no deflection occurs under the impact and dead load of the fresh shotcrete. Nonload-bearing forms may be removed as soon as the shotcrete has achieved final set. Forms are generally not stripped for a few days to avoid superficial damage to the shotcrete. The crew should leave load-bearing forms in place until the shotcrete achieves sufficient strength to support the member. Form removal should be directed by the engineer or the decision to remove forms can be based on satisfactory field strength tests.

5.4—Reinforcement

5.4.1 General—Reinforcement consisting of welded-wire reinforcement (mesh) or plain or deformed reinforcing bars is required in installations where shotcrete will be subject to structural loading. As a structural material, reinforcement in shotcrete is designed using the same criteria as in reinforced concrete. In those applications where shotcrete is not subject to or has limited structural loading, as with interior and exterior linings to 3 in. (75 mm) thickness or in concrete repair where bar reinforcement may already exist, reinforcement in the form of welded-wire reinforcement (mesh) or fibers is recommended. Wire reinforcement or fibers limit the development and depth of cracking resulting from shrinkage and temperature stresses.

Anchorage devices may be used with mesh, fiber-reinforced shotcrete, or both, to prevent debonding. Debonding may be caused by feather-edging, poor or nonuniform bond, deteriorating substrate, or overload. Well-proportioned shotcrete, properly placed against a structurally sound substrate, should not debond at the interface.

Reinforcing bars are rarely used in shotcrete with a thickness less than 1-1/2 in. (40 mm). Mesh may be used in thicknesses down to 1 in. (25 mm). For thin sections of shotcrete, properly sized and proportioned steel fibers may be successfully substituted for standard reinforcement. Using steel fibers in sections thinner than 1/2 in. (13 mm) is not recommended. Some steel fibers will cause some rust staining at the surface, which may effect the appearance of an exposed surface.



Fig. 5.1—Waterproofing panels used as back forms with wood as bottom forms.

5.4.2 Bar reinforcement—Reinforcement obstructs the shotcrete material stream. Best results are usually obtained when the reinforcement is designed and positioned to cause the least interference with the placement of the shotcrete. The nozzle operator's skill becomes increasingly important to ensure adequate encasement of reinforcement as bar size increases or as spacing decreases. If larger-size bars are required by the design, the crew should take care to properly encase the bars with shotcrete ([Section 8.5.8](#)). With congested or large-size reinforcement, the crew should demonstrate that they have the experience to properly encase the reinforcement. Mock-up panels or documented previous experience on work of similar difficulty may demonstrate if the crew can properly encase the steel. In any case, reinforcement should be sized, spaced, and arranged to facilitate the placement of shotcrete and minimize the potential for development of sand pockets and voids. The minimum cover over reinforcement should comply with the job specification or applicable building codes and is usually based on environmental influences.

When existing reinforcing bars are encountered in concrete repair, corrosion products should be a minimum of three times larger than the maximum-size aggregate in the shotcrete. If possible, clearances around an exposed bar should be at least three times the maximum size of the largest aggregate particle in the shotcrete mixture.

Where possible, bars should be spaced to permit shooting at a slight angle from either side of the bar. If the design allows, direct contact of the reinforcing splices should be avoided. Non-contact lapped bars should have a minimum spacing of at least three times the diameter of the largest bar at the splice. For most shotcrete applications with thickness less than 6 in. (150 mm), one layer of reinforcement is usually sufficient, with or without mesh, depending on the application. For greater thickness using several layers of bars, the size and spacing of the bars should be carefully designed and installed for proper and effective shotcreting of deeper recesses. Where several layers of reinforcement are in place before shotcreting, the outermost layers should be sufficiently open to allow the nozzle clear, unobstructed access to the interior of the member (Fig. 5.1).



Fig. 5.2—Shooting through welded-wire mesh cut and bent to follow contours or repair.

Intersecting reinforcing bars should be rigidly tied to one another and to their anchors with 16 gauge (1.3 mm) or heavier tie wire and adequately supported to minimize vibration during shotcrete placement. Vibrations in the reinforcing steel can cause sagging of plastic shotcrete, create voids, and reduce in-place strengths. Large knots of tie wire should be avoided to minimize the formation of sand pockets and voids. Loose mill scale and rust and oil or other coatings that can reduce the bond of the shotcrete to the reinforcement should be removed.

5.4.3 Steel mesh reinforcement—The mesh should be cut to proper size and carefully bent to closely follow the contours of the areas to receive shotcrete (Fig. 5.2).

The reinforcing mesh should be securely tied with 16 gauge (1.3 mm) or heavier tie wire to preset anchors or reinforcing bars. Large knots of tie wire should be avoided to minimize the formation of sand pockets and voids. When sheets of mesh intersect, they should be lapped at least 1.5 spaces in both directions and be securely fastened. In no case should the wires be spaced less than 2 in. (50 mm) apart (Section 5.4.2). When more than one layer of mesh is required, the first layer may be covered with shotcrete before placing the second layer. Some type of anchor or tie should extend to the second layer. Unless the design dictates otherwise, the sheet of mesh should be placed in the center of the shotcrete layer.

5.5—Anchors

Special devices are used in shotcrete work to anchor, support, or space the reinforcement. Some of the factors involved in determining the type, size, and spacing of these devices are: the type of application; its design; the shotcrete thickness; the nature of the original surface; and the type, weight, and geometry of the reinforcement. The maximum recommended spacing of anchors for most applications is 36 in. (900 mm) on-centers-both-ways for horizontal surfaces, 24 in. (600 mm) on-centers-both-ways for vertical and inclined surfaces, and 18 in. (450 mm) on-centers-both-ways for overhead surfaces. If special conditions exist, the design of the anchor spacing and size should be checked for sufficiency in pullout and shear. Anchors or spacers

for reinforcement should be located to provide sufficient clearance around the reinforcement, permit proper cover, and complete encasement with sound shotcrete. Special bowtie connectors are sometimes used with fiber-reinforced shotcretes to provide mechanical connection to the anchors.

5.5.1 Anchoring to steel—Reinforcement can be attached to steel surfaces using mechanical clips, blank nuts welded to the steel, stud-welded devices, slab bolsters, or self-tapping screws; by direct attachment; or by any manner that does not compromise the integrity of the structural member. Clips and bolsters are only used to directly attach mesh to steel. Studs or nuts can be used to attach reinforcing bars or mesh. Drilling holes through structural members to facilitate the anchoring of reinforcement should be avoided. Consult the structural engineer before drilling into structural members or before welding reinforcing steel.

5.5.2 Anchoring to concrete, masonry, or rock—Reinforcement can be attached to concrete, masonry, and rock surfaces using expansion anchor bolts, steel dowels, self-drilling fasteners, and expansion shields. The choice depends to a large degree on the application, type of specified reinforcement, position of work, number and size of anchors, and cost. The manufacturer's recommendations for size, depth of hole, and safe-working loads in shear and pullout should be explicitly followed.

Expansion anchor bolts are the most commonly used concrete anchors. They are available straight and threaded with a nut at the exposed end or without threads with a hooked or L-shaped exposed end. Both styles have some type of expanding sleeve or wedge on the embedded end to provide positive locking action in a predrilled hole. These anchors come in variable lengths so they can be adapted to shotcrete from 1-1/2 to 6 in. (40 to 150 mm) thick.

Self-drilling fasteners and expansion shields may be used and are useful for 6 in. (150 mm) and thicker layers, up nonuniform shotcrete sections, and where multiple layers of reinforcement are specified.

Steel dowels or reinforcing bars are used in structural shotcrete applications when sections are 6 in. (150 mm) or thicker, and heavy cages of reinforcing bars have to be supported and anchored. They are also used for anchoring shotcrete to rock. They should be set sufficiently deep to meet pullout criteria and installed using a nonshrink cementitious grout, epoxy, or polyester resin.

5.5.3 Anchoring to wood—Reinforcement may be attached to wood surfaces using individual bar chairs, slab bolsters (continuous chairs), or nails. They should be positioned to provide proper cover and encasement by the shotcrete. Bolster legs should be trimmed off when they are adjacent or parallel to reinforcement. If the wood surface is a removable form, nails should not be used and the chairs and bolsters should be plastic-tipped to eliminate rust on the formed surface. Reinforcing bars or individual wires in mesh should not coincide with the longitudinal wire of a slab bolster (Fig. 5.3).

5.6—Alignment control

Alignment control is necessary to establish line and grade in shotcrete construction and to ensure that proper and uniform

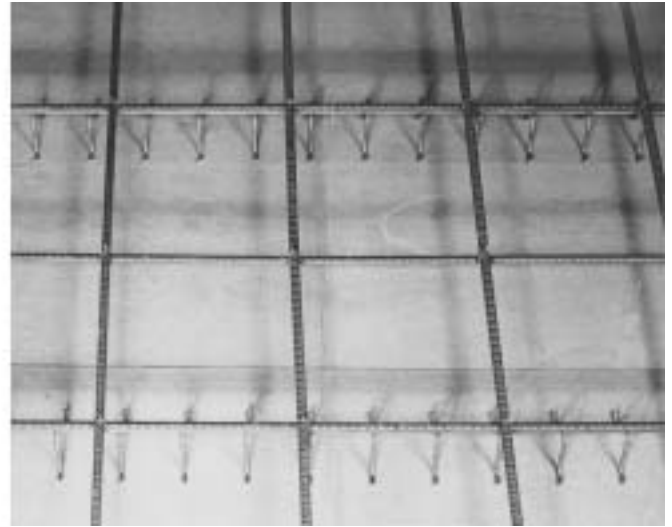
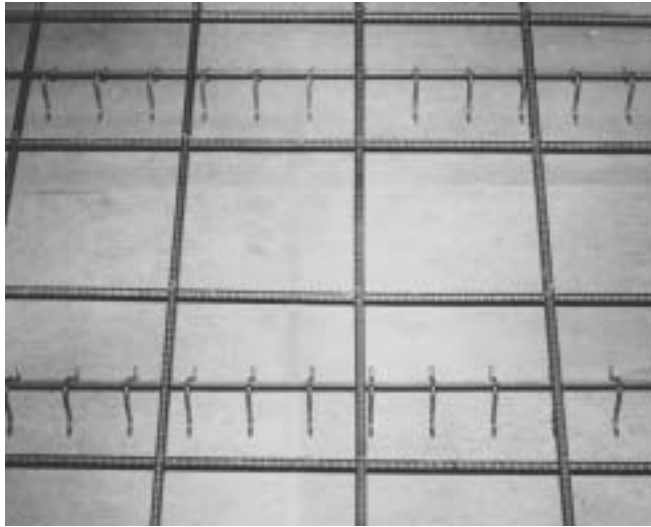


Fig. 5.3—Positioning slab bolsters. Correct (left) and incorrect (right) method for placing continuous chairs or slab bolsters. (To avoid sand pockets, the bolster wire should not be adjacent or parallel to a wire mesh.)

material thickness and cover are maintained. Alignment control is accomplished by the use of ground wires, guide strips, depth gauges, depth probes, or conventional forms.

5.6.1 Ground wires—Ground wires consist of 18 or 20 gauge (1 or 0.8 mm) high-strength steel wire, called “music” or “piano” wire that can be combined with a device that places the wire under suitable tension (not all situations require a tensioning device). Ground wires are the most convenient means to establish line and grade when forms are used to shoot against. Wires may be used individually to establish corners, while several parallel wires in combination may be spaced 2 to 3 ft (0.6 to 0.9 m) apart to provide screed guides for flat areas (Fig. 5.4). For work with tight tolerances, space the ground wires 12 to 18 in. (300 to 450 mm) apart.

5.6.2 Guide strips—Guide strips consist of wood lath usually no larger than 1 x 2 in. (25 x 50 mm) connected by crosspieces at 2 to 3 ft (600 to 900 mm) intervals. Guide strips serve as an excellent method of alignment control in both repair and new shotcrete construction. Chamfered edges are readily attained using a chamfer strip at the corner of the guide strips.

5.6.3 Depth gauges—Depth gauges are small metal or plastic markers attached to or installed perpendicularly in the substrate or backup material at convenient intervals and heights. Depth gauges provide a preset guide to the thickness of the shotcrete and are positioned approximately 3/4 in. (20 mm) below the finish coat of shotcrete. They are normally left in place, provided they do not affect the integrity of the application (Fig. 5.5). Any gauge that is normal to the surface and is tied to the reinforcement will provide a conduit for moisture and allow subsequent corrosion. Gauges that are tied to reinforcement should be cut back 3/4 in. (20 mm) to prevent a moisture conduit.

5.6.4 Depth probes—Depth probes are used in situations where there is greater latitude in the finish tolerance requirements. They are usually made of 12 to 14 gauge (2.1 to 1.6 mm) steel, and marked with the specified shotcrete



Fig. 5.4—Shooting concrete using ground wires as a guide to bring materials to line and grade.



Fig. 5.5—Ground wire attached to depth gauge, which is tied to reinforcing steel and will be left in place.

thickness. Probes are inserted into the shotcrete until the substrate is reached, indicating the depth of shotcrete. Probes should only be used if puncture holes can be tolerated.

5.6.5 Formwork—The use of conventional forms in shotcrete work is the exception rather than the rule. Conventional forms may prevent adequate escape of air, resulting in the formation of

voids. When conventional forms are used, however, they usually provide automatic alignment control, eliminating the need for special devices for line and grade control. The nozzle operator should control the nozzle technique to prevent the formation of sand pockets and other defects.

5.7—Joints

5.7.1 Contraction/expansion joints—Joints may be provided by the prepositioning of full-thickness strips, usually wood or steel, that are left in place, or by tooling a groove in the plastic shotcrete, or by saw-cutting the shotcrete shortly after it has achieved final set. Joint spacing depends on the application and its design, and should be designated on the plans. In practice, the spacing usually varies from 15 to 30 ft (5 to 9 m). When shooting over an existing joint, the new joints should coincide with the existing joints.

5.7.2 Construction joints—Square construction joints are generally avoided in shotcrete construction because they form a trap for rebound and overspray. Construction joints are usually constructed at a 45-degree angle. Where the joint will be subjected to compressive stress, however, square joints are sometimes required, in which case the crew should take the necessary steps to avoid or remove trapped rebound at the joint. Before applying additional shotcrete, the entire joint should be thoroughly cleaned and wetted, and allowed to dry to a saturated surface-dry condition.

When a section of shotcrete is left incomplete at the end of a shift, provisions should be made to ensure the joint will not develop a plane of weakness at this location. Therefore, the joint is tapered to an edge, usually about 1/2 the thickness of the shotcrete, a maximum of 1 in. (25 mm). A better appearing joint may be constructed by sloping to a shallow edge using a 1 in. (25 mm) thick board placed flat.

5.8—Protection of adjacent surfaces

Rebound, overspray, and dust resulting from the shotcrete application can contaminate adjacent structures, equipment, and grounds. This problem is especially aggravated on windy days. Therefore, it is important to evaluate the effect of the shotcrete application on adjacent surfaces and make the necessary arrangements to protect them. Ideally, isolate the shotcrete operation from areas or surfaces needing protection. Although this is not always possible, protection can take the form of a cover, masking materials, or temporary protective coatings. Covers may include plywood or similar materials, polyethylene film, or drop cloths. Masking materials are usually used in conjunction with the above materials. Temporary protective coatings include grease, diesel oil, and other materials that can be removed without too much difficulty.

If none of the above are practical, adjacent surfaces should be cleaned and washed before the rebound and overspray hardens. The protection of adjacent surfaces should include concern for the buildup of overspray, rebound, and dust on surfaces that receive shotcrete. If these materials are allowed to build up, they will cause low shotcrete strength and interfere with bonding.

CHAPTER 6—PROPORTIONING AND PRECONSTRUCTION TESTING

6.1—Introduction

Shotcrete mixtures are usually proportioned to attain a specified compressive strength. The main reasons for variations of in-place strength are the nature of the shotcrete process, type of delivery equipment, and quality of workmanship. This is especially true of dry-mix shotcrete, where the nozzle operator is not only responsible for the proper placement technique but also regulates and controls the water content—a variable that can cause fluctuations in strength.

In certain applications, particularly those with thin layers of shotcrete, properties other than compressive strength may be more important for a successful application. Qualities such as permeability and durability may have to be considered, requiring some alteration in the mixture proportions.

There is a wide range of shotcrete equipment, as described in [Chapter 3](#), and no single mixture proportioning criteria can be applied in all cases. Before proportioning a mixture, the following should be considered:

- Preferred characteristics of the shotcrete work and the constraints involved;
- The type of specification selected for the work, performance, or prescription; and
- The type of shotcrete placing equipment appropriate for the work: wet-mix or dry-mix, each with or without coarse aggregate.

6.2—Performance versus prescription specification

There are two general approaches to specifications: the performance method and the prescription method. A performance specification should be used whenever possible. When possible, the installer should be consulted on the types of cement, aggregate, and shotcrete equipment available and the shotcrete properties that can be achieved with local materials.

6.2.1 Performance specification—The performance specification states the required quality of shotcrete. Applicators decide how to achieve the specified performance. Typically, these parameters might be specified:

- Cement type;
- Aggregate gradation;
- Compressive strength at specified age;
- Slump, if wet-mix;
- Air content, if wet-mix;
- Specific performance requiring use of admixtures; and
- Specific performance of fiber shotcrete.

In many applications, specifying compressive strength alone is adequate.

Mixture proportions should be developed as part of the preconstruction test program or be based on previous experience.

6.2.2 Prescription specification—The prescription specification should only be used for special job requirements or to limit the work to a particular type of shotcrete. Typically, the following would be specified:

- Cement type and content;
- Aggregate gradation, mass, or volume;

- Admixtures and dosage;
- Slump, if wet-mix;
- Air content, if wet-mix; and
- Fiber type and content.

This type of specification can be simplified for dry-mix application by specifying cement-aggregate proportions such as 1:4.

6.3—Proportioning of shotcrete mixture

6.3.1 General—Many principles of normal concrete technology can be applied to shotcrete, particularly the wet-mix process. Differences, however, should be recognized before proportioning mixtures. In-place shotcrete has a higher cement factor than the proportion mixture because of rebound. Rebound also eliminates a certain percentage of coarse aggregate, resulting in a finer aggregate gradation in place. This effect, plus the fact that the cement content of shotcrete mixtures is usually higher than in conventional concrete, increases the potential for shrinkage problems and the development of surface cracking (U.S. Bureau of Reclamation 1975; Ryan 1973).

It is not practical to conduct laboratory trial mixtures for the dry-mix process, and there are also problems in duplicating as-shot conditions for the wet-mix process. Therefore, field trials and preconstruction testing, as described in [Section 6.4](#), should be used for qualifying mixture proportions.

The mixture proportions should be designed to produce sample strengths higher than the design strength. Refer to ACI 214R for guidance.

6.3.2 Wet-mix process—Proportioning can be done in accordance with ACI 211.1 with the aggregate content correction for pumped concrete.

At times, the coarse-aggregate content recommended by this proportioning system may be somewhat high, but generally, the maximum content consistent with placing restraints should be used. It is not advisable to incorporate more than 30% coarse aggregate (percent mass of fine plus coarse aggregate) in the mixture.

In general, a typical wet-mix shotcrete mixture proportion will have seven to eight sacks (390 to 450 kg/m³) of cement, cement plus fly ash, or other pozzolan per cubic yard of concrete. Aggregate will consist of 20 to 30% pea gravel, 1/2 in. (13 mm) maximum, 70 to 80% concrete sand or sands with a combined sand fineness modulus of 2.5 to 2.9, a water-reducing admixture, and a water content that will yield a slump of 1-1/2 to 3 in. (40 to 75 mm).

The concrete should be proportioned so that it is pumpable with at least 15 to 30% fine aggregate passing the No. 100 (0.15 mm) screen and a maximum nominal-size aggregate less than 1/3 the diameter of the material hose.

The slump of the wet-mix process shotcrete should generally be the minimum that can be handled by the pump. A slump of 1-1/2 to 3 in. (40 to 75 mm) is normally suitable. Excess slump results in a weaker shotcrete and sloughing when the shotcrete is placed on vertical or overhead surfaces. A mixture that is too stiff may be difficult to pump and shoot and may not fully encapsulate reinforcement.

For durability and pumpability, *w/cm* for normal wet-mix shotcrete typically ranges from 0.4 to 0.5 without admixtures. Lower *w/cm* are possible with the use of water-reducing admixtures (all types).

Wet-mix shotcrete should be air-entrained when the shotcrete will be subjected to freezing and thawing in saturated conditions. A minimum total air content of 6% in the concrete before pumping is generally desirable (Sections [1.6.5](#) and [2.7.2](#)).

Shotcrete will lose slump during pumping. Entrained air is also lost in pumping if the concrete free falls in the pump system. These losses depend on the length of line, type of pump, and initial levels of air content. Additional entrained air is lost during shooting as indicated in [Section 2.7.2](#).

6.3.3 Dry-mix process

6.3.3.1 Aggregate proportion—Aggregates should be a blend of sizes as required to produce a combined grading within the limits of [Table 1.1](#).

The particle-size distribution of aggregates in place will be markedly finer than when batched because the larger particles have proportionally larger rebound loss. Rebound losses can cause an approximate 30% change in the cement-to-aggregate ratio. A mixture of 1:3 entering a gun can result in a 1:2 mixture in place.

6.3.3.2 Mixture proportions—There is no recognized rational method of proportioning dry-mix shotcrete for strength. Applicators, who use the same consistent sources of materials and can provide adequate proportioning data from previous experience, are typically permitted to use proven mixtures. This approach is appropriate for many small projects where the cost of preconstruction testing is prohibitive. Preconstruction testing is required if previous data are not available, properties other than strength affect the design criteria, or if design requirements vary from one portion of the work to another. Preconstruction testing to determine mixture proportions is also advisable if there is some question as to the gradation or quality of the aggregate and the effect of the amount and spacing of the reinforcing steel.

It is possible to produce dry-mix shotcrete of extremely high strength if high cement contents and quality aggregates are used and if a high degree of in-place compaction is achieved. Compressive strengths as high as 12,000 psi (80 MPa) have been reported for trial mixture panels, and 10,000 psi (70 MPa) strengths are commonly quoted in the literature. Strengths higher than 5000 psi (35 MPa), however, should not be specified except in carefully controlled projects where adequate research into the potential performance of local materials has been performed.

For coarse-aggregate shotcrete mixtures, [Table 6.1](#) illustrates some typical data on the effect of as-batched cement content on strength of typical dry-mix shotcrete mixtures.

Field trials are required to determine the final cement content. The method of evaluating the in-place cement content and strength of shotcrete is detailed in ACI 506.4R.

One method of preliminary proportioning is to establish the wet density of the mixture (from the aggregate supplier's data or aggregate relative density tests) and proceed as shown in the following example:

Table 6.1—Strength versus cement content

Specified 28-day compressive strength, psi (MPa)	Cement content as batched, lb/yd ³ (kg/m ³)
3000 (21)	500 to 650 (295 to 385)
4000 (28)	550 to 700 (325 to 415)
5000 (35)	650 to 850 (385 to 505)

Specified requirements:

28-day compressive strength: 4000 psi (28 MPa)
Maximum-size aggregate: 1/2 in. (13 mm)

English unit example

Cement, Type I
Preliminary design: Assume in-place wet density 145 lb/ft³
Therefore: total weight per cubic yard = 145 × 27 = 3915 lb/yd³
Select cement content as 650 lb/yd³
Estimate *w/cm* as 0.35 (the *w/cm* for dry-mix shotcrete is typically between 0.30 and 0.40)
Therefore: water required is 230 lb/yd³
Aggregate content (coarse aggregate + sand) = 3915 – 650 – 230 = 3035 lb/yd³

Metric unit example

Cement, Type I
Preliminary design: Assume in-place wet density 2320 kg/m³
Select cement content as 385 kg/m³
Estimate *w/cm* as 0.35 (the *w/cm* for dry-mix shotcrete is typically between 0.30 and 0.40)
Therefore: water required is 135 kg/m³
Aggregate content (coarse aggregate + sand) = 2320 – 385 – 135 = 1800 kg/m³

The amount of water calculated above should be adjusted for surface moisture in the aggregate. Admixture dosages have not been included; refer to [Section 2.7](#).

6.4—Preconstruction testing

For preconstruction studies, shooting test 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. A panel is fabricated by shooting onto a back form of heavy plywood or steel plate in accordance with ASTM C 1140. A separate panel should be fabricated for each mixture proportion being considered, and also for each shooting position to be encountered in the structure such as horizontal, vertical, or overhead. Results of previous tests with similar materials, mixture proportions and applications may be acceptable to the engineer instead of preconstruction testing.

Separate test panels should be fabricated for mixture proportion evaluation and for nozzle operator qualification. The mixture proportion test panels should be 24 x 24 x 3-1/2 in. (610 x 610 x 89 mm) with flared sides and no reinforcement. The nozzle operator qualification test panel should be large enough to simulate the actual project conditions with a minimum size of 30 x 30 x 3 in. (760 x 760 x 75 mm) and should be reinforced to simulate the size and complexity of the reinforcement to be shot on the project. Both types of test panels should be cored or sawn to obtain 3 in. (75 mm) diameter

cores or 3 in. (75 mm) cubes. The unreinforced cores or cubes should be tested for compressive strength. Cube strengths may be reported as determined or converted to equivalent cylinder strengths by multiplying by 0.85. ACI 506.2 lists requirements for testing.

The cut surfaces of the specimens should also be carefully examined, and additional surfaces should be exposed by sawing or breaking the panel when necessary to check the soundness and uniformity of the material. All cut and broken surfaces should be dense and free from laminations, voids, and sand pockets.

Tests for modulus of rupture, flexural toughness of fiber-reinforced shotcrete, absorption, drying shrinkage, resistance to freezing and thawing, and other properties may also be conducted if required by the specifications, using appropriate specimens cored or sawed from the panel. All tests should be performed by an agency meeting the requirements of ASTM E 329.

The procedures described previously should determine the optimum proportions to consistently achieve the result specified. Once the mixture proportions have been established by the engineer, they should be monitored. It may be permissible, however, to make the test panels concurrent with the start of construction, or cores can possibly be taken from the first shotcrete placed in the structure. On relatively small jobs and where the materials, mixture proportions, equipment, and personnel have given satisfactory results on previous work, preconstruction studies may not be justified.

CHAPTER 7—BATCHING AND MIXING

7.1—Introduction

Proper batching and mixing are extremely important steps in the production of quality shotcrete.

7.2—Batching

Shotcrete materials can be batched by weight or volume. For projects with difficult access, small volumes of shotcrete or low placement rates, volume batching of aggregate, and cement batching by bag may be more practical and is common in some areas. It is also possible to use preblended dry cement and aggregate for dry-mix. The crew should predampen the batch before introducing it to the shotcrete delivery equipment unless a long nozzle (as described in [Section 3.7.1](#)) is used.

Specifications for batching tolerances are available in ASTM C 94 for weight batching and ASTM C 685 for volume batching. These tolerances are seldom necessary for shotcrete batching, as experience shows that quality shotcrete can be produced with less restrictive tolerance values. ACI Committee 506 recommends that the tolerances in ASTM C 94 be increased to:

- Cement: ±2% of mixture proportion weights;
- Aggregate: ±4% of mixture proportion weights; and
- Admixtures: ±6% of mixture proportion weights.

Instead of weighing, cement may be measured by bags (94 lb [43 kg]), while the aggregates may be batched volumetrically, provided weight checks are made as described previously. Weight batching can be accomplished at a central concrete

plant or near the job site. Volumetric batching equipment, such as that associated with mobile mixer units, are available for high production work (Section 3.5.2). A less-convenient method for field batching uses wheelbarrow scales. Weight-calibrated containers may also be used to manually proportion mixtures.

In dry-mix shotcrete, the moisture content of the fine and coarse aggregates should be such that the aggregate-cement mixture will flow at a uniform rate without slugging or hose plugging. The optimum moisture content is generally within the range of 3 to 7%, or more if silica fume is used. The sand should be dried or wetted as required to bring the moisture content within that range, and large fluctuations in moisture content should be avoided.

7.2.1 Admixtures—Admixtures for shotcrete are available in powder and liquid form. The method of introducing the admixtures into the shotcrete mixture depends primarily on the nature of the admixture, its intended use, and the method of shotcreting. In the dry-mix process, powdered admixtures are added during the batching or mixing stage, while liquid admixtures are introduced at the nozzle with the mixing water (Section 3.8.11.1). In the wet-mix process, powdered or liquid admixtures can be added at the batching stage or liquids added at the nozzle in the air supply using a proportioning device. Quick-set accelerators are only introduced at the nozzle in the wet-mix process (Section 3.8.11.2).

7.2.2 Fibers—The use of steel and synthetic fibers in both wet-mix and dry-mix shotcrete is described in Section 2.8.1. It is important that fibers be uniformly distributed throughout the in-place shotcrete mixture. Whichever shotcrete process is used, fibers are usually introduced by batching at the mixing stage (Section 3.8.10). Preconstruction trials are usually recommended for manual feeding to develop procedures that will minimize balling or clumping of the fibers and ensure uniform distribution of the fiber throughout the mixture.

7.2.3 Prepackaged dry-mix material—Prepackaged dry-mix ingredients are advantageous in circumstances such as:

- Access for bulk material is limited;
- Workspace is limited;
- The volume of material does not justify bulk material;
- The site is remote or difficult to access; and
- Specialized or proprietary ingredients have been specified that might be more easily controlled in a bagging/packaging facility.

Project requirements will dictate the effectiveness of prepackaged materials. As with any concrete project, control of the batching for uniformity and accuracy is essential and should be well established before the work begins. Most prepackaged materials require predampening before shooting. (Consult manufacturer's recommendations.) Refer to ASTM C 1480 for requirements for packaged material.

7.3—Mixing

A description of mixing equipment available for most shotcrete applications appears in Section 3.5. The mixing equipment should be capable of thoroughly mixing all ingredients (except water in the case of dry-mix equipment) in sufficient quantity to maintain placing continuity and

provide adequate production rates. It is also good practice to screen all material exiting from the mixer to exclude lumps of material, oversized aggregate, and other foreign objects that could cause plugs in the pump or hoses.

7.3.1 Dry-mix process—The mixer should distribute the cement and admixtures homogeneously throughout the mixture, thoroughly coating the aggregate. Proper coating of the aggregate is dependent on adequate predampening moisture, mixing time, and shape and configuration of the mixing blades, paddles, or augers. Proper predampening promotes smoother flow through the hose and reduces dusting.

A uniform color (no sand streaks) is a visual indication that the shotcrete is thoroughly mixed. Vibratory screening of the shotcrete mixture on exit from the mixer tends to reduce the presence of these streaks, though it is not a cure-all for poor mixing practices. Sand streaks should be avoided because they can create sand pockets and laminations.

A crude but effective test for determining proper predampening is the ball-in-hand test. A small amount of mixture is placed in the hand and squeezed tightly. When the hand is opened, the mixture may crumble into discrete particles, which indicates too little predampening moisture. If the material holds together or cracks but remains essentially whole, there is enough moisture. If moisture comes off on the hand, there is too much moisture in the mixture.

For optimum strength and setting time, a shotcrete mixture containing damp sand should be gunned within 45 minutes after mixing. Prehydration of the cement with the moisture in the sand will reduce early and ultimate strength and extend setting time of both normal and accelerated shotcrete. A mixture that has dried out and becomes caked should be discarded. Rebound should never be reused.

7.3.2 Wet-mix process—The required mixing time will depend on the mixture being used and the efficiency of the mixer. Mixing should conform to ACI 304R and ASTM C 685. When concrete is used, it should conform to ASTM C 94. Delivery of concrete at the desired slump and uniformity from batch to batch is essential for a good shotcreting operation, especially in vertical and overhead applications. A batch should be shot within the time specified in ACI 506.2. Discarded shotcrete material should not be used.

CHAPTER 8—SHOTCRETE PLACEMENT

8.1—Introduction

The importance of using proper placement techniques to ensure quality shotcrete cannot be overstated. This chapter represents the best current practice; however, practice varies geographically and acceptable variations exist. The information contained herein supplies guidance and direction to the owner, designer, applicator, inspector, and other interested parties. ACI 506.2 contains supplementary information and procedures to aid in achieving the desired result.

Chapter 5, Preliminary Procedures, covers surface preparation, forms, anchors, reinforcement, alignment, joints, and protection of adjacent surfaces. It should be referred to in conjunction with this chapter because much of the information it contains complements the subject of shotcrete placement.

8.2—Special applications and mixtures

Shotcrete is sometimes required to have special properties such as low density, insulating qualities, or resistance to heat or acids. These may dictate the use of special aggregates, cements, or admixtures.

Lightweight aggregate mixtures have been shot for wall and floor construction.

Shotcrete is frequently employed for fireproofing structural steel members, and lightweight aggregates are sometimes used in the mixture.

Calcium-aluminate (high-alumina) cement is preferred over portland cement for certain applications where rapid hardening is required or where heat resistance or acid resistance is desired (Section 2.3.2). For refractory linings, calcium-aluminate cement is commonly used in combination with a heat-resistant aggregate.

Successful shotcreting of special mixtures may require different placement techniques and methods of installation. Only applicators with the requisite expertise and experience should be used.

Additional information on refractory applications may be found in ACI 547R and ACI SP-57.

8.3—Preliminary procedures

8.3.1 General—Before starting shotcrete placement, it is important that materials and shotcrete equipment are both ready to ensure a smooth-running and efficient operation.

8.3.2 Materials—In dry-mix field mixing, cement should be fresh, uncaked, and in unbroken bags. Aggregate should be clean, uncontaminated, and contain sufficient moisture—usually 3 to 7%—to minimize dusting, overspray, and rebound. Predampening of the aggregate may be required, though too much moisture can cause plugging of the material hose during shotcreting. Dry-mix material batched and supplied from a centrally located concrete plant may be used if the mixture can be used within 45 minutes of the time of mixing, and preconstruction testing determines the product meets design criteria. (For hot-weather shotcreting, 15 minutes would be the limit [Section 8.9].) Allowing damp sand to remain in contact with the cement for prolonged periods will result in reduced strength, set retardation, and increased rebound (Section 7.3.1).

Materials for the wet-mix process should meet the requirements of ASTM C 94.

Successful prior use of materials in the same combinations in a particular mixture should be sufficient evidence of its shooting capabilities.

8.3.3 Equipment—Proportioning, mixing, and shooting equipment should be clean to ensure quality shotcrete. The crew should regularly check proportioning equipment to be certain that the proper mixture is being obtained. From an economic standpoint, it is in the applicator's interest to keep equipment in excellent operating condition to maximize production and minimize slowdowns, breakdowns, and plug-ups (hose blockage).

8.3.4 Cleaning and prewetting—As outlined in Section 5.2, surface preparation may occur days or weeks before the shotcreting operation. If so, the substrate should be recleaned by

washing it with water just before shotcreting. In the dry-mix process, this can be accomplished with an air-water blast from the nozzle. The substrate surface should be at a saturated surface-dry condition just before shotcrete application.

If the substrate is extremely porous, it should be prewetted for some time before shotcreting to minimize absorption of mixing water from the shotcrete mixture.

8.4—Shotcrete equipment procedures

As described in Chapter 3, the dry-mix and wet-mix processes use different types of delivery equipment with different operating characteristics that can affect the choice of shotcreting process, the application, and quality of the shotcrete.

8.4.1 Dry-mix process—Initially, the gun operator introduces only compressed air into the delivery hose, slowly adding mixture material at the direction of the nozzle operator. The gun operator should balance the air and material flow so as to provide a steady, uninterrupted flow of material from the nozzle. The nozzle operator controls the volume of water added to the nozzle so that the material is properly wetted. Stopping the operation involves shutting off the material feed, and when the air delivery hose blows clear, shutting off the water and then the air.

8.5—Application of shotcrete

8.5.1 General—The quality of shotcrete application depends to a large extent on the gun operator, pump operator, and nozzle operator; control of mixing water; nozzle velocity; and nozzle technique. In each case, the expertise and experience of the responsible crew member determines the adequacy and quality of the operation (ACI Committee E 703 2000).

8.5.2 Gun or pump—In the dry-mix process, proper gun operation is critical to ensure a smooth, steady flow of material through the hose and nozzle. If a suitable balance of air and material flow is not maintained, slugging, plug-ups, or excessive rebound may occur. Pulsating and intermittent flow of shotcrete material causes underwetting or overwetting of the mixture and requires the nozzle operator to quickly adjust the water, manipulate the nozzle, direct it away from the work, signal for air, or stop. The crew should remove unsuitable shotcrete resulting from slugging.

In the wet-mix process, slugging does not occur unless the as-delivered material is not properly mixed or if accelerators are added at the nozzle. Small amounts of accelerator can react with cement dust/residue, which creates a buildup of material that causes slugging. The pump operator should regulate the pump to evenly deliver the wet-mix at the rate required for the particular shotcrete application and monitor the concrete being delivered to the pump hopper for correct consistency.

8.5.3 Control of mixing water—In the dry-mix process, the nozzle operator should add enough water at the nozzle so the surface of the in-place shotcrete has a slight gloss. The nozzle operator can change the water content instantaneously as needed. Depending on the position of the work, too much water can cause the shotcrete to sag, slough, puddle, or drop

out. Dropouts may also occur in overhead work where too much material is gunned or hung in one location at one time. Too little water leaves a dry, dark, sandy surface with no gloss. This condition increases rebound, increases the likelihood of sand pockets, makes finishing difficult, and can produce weak and laminated shotcrete. For effective water control, the water pressure at the nozzle should be substantially greater than the air pressure.

The wet-mix nozzle operator has no control over the water content. The slump of the concrete mixture should be maintained between 1-1/2 and 3 in. (40 to 75 mm). Below a 1-1/2 in. (40 mm) slump, rebound becomes more pronounced, and shotcrete will not readily flow around reinforcement, whereas shotcrete at slumps above 3 in. (75 mm) may develop sagging, puddling, or dropouts in vertical and overhead applications. Higher-slump material may be appropriate for horizontal surfaces.

8.5.4 Impact velocity—The velocity of the material at impact is an important factor in determining the ultimate properties of the shotcrete and to adequately encase reinforcement. For most applications where standard nozzle distances of 2 to 6 ft (0.6 to 1.8 m) are used, the impact velocity is a little less than the material velocity at the nozzle. At greater nozzle distances, the impact velocity is considerably less, and it may be necessary to increase the nozzle velocity so that the impact velocity will suit the requirements of the application. Greater distances are sometimes allowed with remote-controlled manipulator arms.

With dry-mix shotcrete, the factors that determine material velocity at the nozzle are volume and pressure of available air, hose diameter and length, size of nozzle tip, type of material, and the application rate it is being gunned at. These factors allow for great flexibility and versatility because large, intermediate, or small volumes of material can be gunned at low, medium, and high velocities according to the immediate needs of the application. Small or large variations in flow, water content, and velocity can be made on order from the nozzle operator.

The type of application and the limitations of workability required for pumping predetermine the water content in wet-mix shotcrete. This usually limits the use of this method to applications with low and medium velocities and large volume, although smaller-volume wet-mix pumps are now available.

8.5.5 Nozzle technique and manipulation—Proper nozzle operation is physically demanding. Nozzle technique for wet-mix and dry-mix processes is generally similar, both requiring considerable attention to detail. Because the capabilities of wet-mix and dry-mix procedures and equipment are different, each requires a somewhat different expertise from the nozzle operator, and he or she should not assume that the nozzle techniques are exactly interchangeable, especially the finer details of the skill (Crom 1978).

8.5.6 Thickness and work position—Shotcrete may be applied in layers or a single thickness, depending on the position of the work. Overhead work is typically gunned in layers just thick enough to prevent sagging or dropouts, usually 1 to 2 in. (25 to 50 mm). Vertical surfaces may be applied in

layers or as a single thickness, while horizontal or flat surfaces are usually gunned in a single thickness. In any case, the thickness of a layer is governed mainly by the requirement that the shotcrete should not sag. Sags or sloughs that go undetected and not removed can hide internal cracks and hollows that make the shotcrete vulnerable to water penetration, freezing-and-thawing action, and reduction or loss of bond between layers.

8.5.7 Shooting—Each layer of shotcrete is built up by making several passes of the nozzle over a section of the work area. Whenever possible, sections should be gunned to their full design thickness in one layer, thereby reducing the possibility of cold joints and laminations. The shotcrete should emerge from the nozzle in a steady, uninterrupted flow. Should the flow become intermittent for any reason, the nozzle operator should direct the stream away from the work until it becomes constant. The distance of the nozzle from the work, usually between 2 and 6 ft (0.6 to 1.8 m), should be such as to give best results for work requirements. As a general rule, the nozzle should be held perpendicular to the receiving surface but never oriented at more than 45 degrees to the surface (Fig. 8.1(a) and (b)).

When the nozzle is held at too great an angle from perpendicular, the shotcrete rolls or folds over, creating an uneven, wavy-textured surface that can trap greater amounts of rebound, and overspray. This process, known as rolling, is not a recommended nozzle technique, wastes material, and may create porous and non-uniform shotcrete.

To uniformly distribute the shotcrete and minimize the effect of slugging, the operator should direct the nozzle perpendicular to the surface and rotate it steadily in a series of small oval or circular patterns (Fig. 8.2).

Waving the nozzle quickly back and forth changes the angle of impact, wastes material, increases overspray, and unnecessarily increases the texture roughness of the surface.

8.5.8 Encasing reinforcement—Reinforcing bars interrupt the material stream, so the area behind the bar is not compacted by the following stream of shotcrete material. This area behind reinforcement needs to be filled either by material that flows around the bar or by having the stream directed behind the bar. A shotcrete mixture that has good impact and sufficient plasticity will flow around and completely encase the reinforcement. High impact velocity will also force stiffer material around the reinforcement. The nozzle operator can increase the impact velocity by moving closer to the work. Sufficient plasticity is more important than high impact velocity when encasing reinforcement. Observing the face of the reinforcement during application of shotcrete will provide an indication of the quality of encasement. When deformations (ridges) on the face of the reinforcement are clearly visible, it is a good indication that material is flowing around the reinforcement, and the reinforcement should become adequately encased.

Larger reinforcement requires a more plastic mixture for good encasement, and the angle of the material stream should be adjusted to ensure the area behind the reinforcement is compacted. For even larger or congested reinforcement, the nozzle operator may have to reduce the air volume and insert

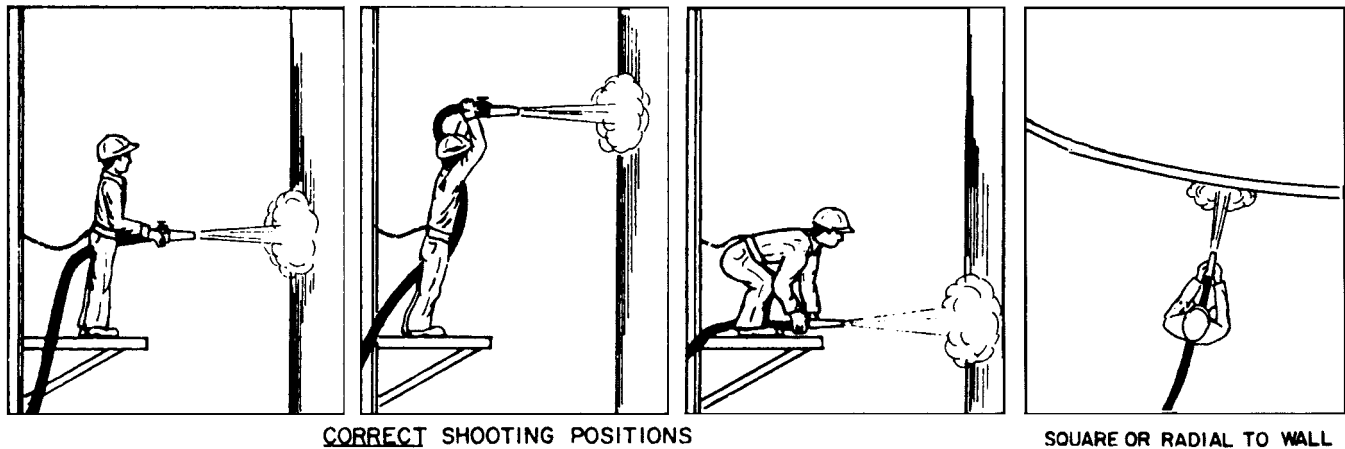


Fig. 8.1(a)—Shooting positions.



Fig. 8.1(b)—Correct shooting position.

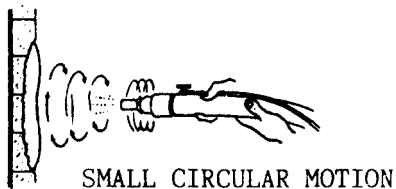
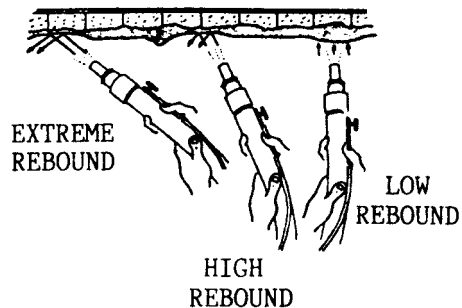
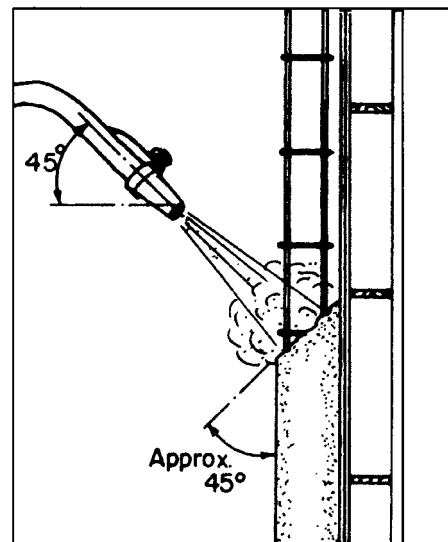


Fig. 8.2—Manipulating the nozzle to produce the best shotcrete.

the nozzle tip behind the bars. When working in close, the volume and velocity of the shotcrete should be reduced to prevent a blowback of air that will create voids. Voids will develop if sloughing occurs behind the bars.

When shooting walls in vertical layers, the application should begin at the bottom and fill corners. The first layer should, if possible, completely encase the reinforcement adjacent to the form. Subsequent layers should be thin



CORRECT SHOOTING THICK APPLICATIONS

Fig. 8.3—Bench or shelf shooting of concrete.

enough so that sloughing and sagging does not occur. The allowable thickness is dependent primarily on the plasticity of the shotcrete and the texture of the receiving surface.

The other method of constructing a vertical wall (over 6 in. [150 mm]) is to shelf or bench shoot. Instead of shooting directly against the vertical surface, a thick layer of material is built up at the bottom. The nozzle stream is directed into the top surface that is maintained at an approximately 45-degree slope (Fig. 8.3). The lift height is dependent on the slump of the shotcrete, reinforcement spacing, receiving surface texture, weather, and other factors. Shotcrete lift height should be limited to prevent sloughing and sagging. The timing between lifts is also dependent on many variables. Successive lifts can be placed when the previous lift is sufficiently stiff to support the weight of the next lift (Fig. 8.4).

When shooting horizontal slabs, the operator should hold the nozzle at a slight angle from the perpendicular so that the rebound is blown onto the completed portion where it can be removed.



Fig. 8.4—Wet shooting around reinforcing bars.

When inside corners or other projections are part of the area to be shotcreted, they should be gunned first and continuously built up as the layers become thicker (Fig. 8.5).

Shooting into corners first will prevent rebound and overspray from forming a porous layer. In the dry-mix process, slight overwetting of the initial layer helps bond and reduces rebound.

A clean receiving area free of rebound, overspray, and other debris should be maintained. The use of an air blowpipe is helpful, but preventive or corrective measures by the nozzle operator are the most effective procedure (Fig. 8.6).

8.5.9 Multiple layers—When a layer of shotcrete is to be covered by a succeeding layer, it should first be allowed to harden slightly or stiffen. Then all loose, uneven, or excess material, glaze, laitance, and rebound should be removed by brooming, scraping, or other means. Sandblasting or water-blasting should remove any undesirable surface deposits that have taken a final set. The surface can be cleaned with an air-water blast if using dry-mix shotcrete. In addition, the surface may be thoroughly sounded with a hammer for hollow areas resulting from rebound pockets or lack of bond. Visible hollows, sags, or other defects should be cut out. Surfaces to be shot should be in a saturated surface-dry condition. Curing compounds or other bond-breaking materials should not be applied to surfaces that will be covered by an additional layer of shotcrete. It is good practice to leave the surface open, rough, and highly textured to improve the bond of the succeeding layer (Fig. 8.7).

8.5.10 Structural shotcrete—It is sometimes advantageous to use shotcrete for the construction of heavy structural members in new construction and to bond columns, girders, or walls to existing construction (Fig. 8.8).

The successful use of shotcrete in structural sections requires careful planning, forming, skill, and continuous care in application. The nozzle size and rate of feed should be limited as necessary to permit full nozzle control and produce a uniform, dense application, even in tight places.

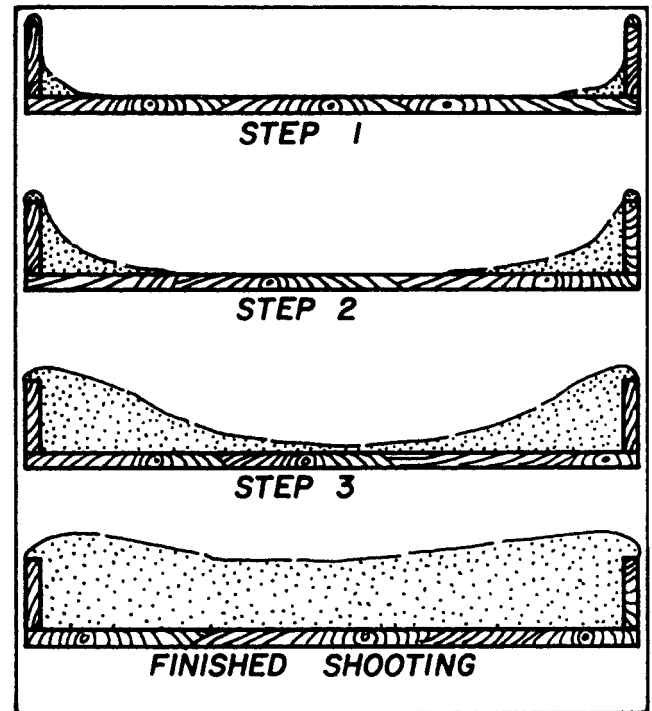


Fig. 8.5—Proper procedure for shooting corners.

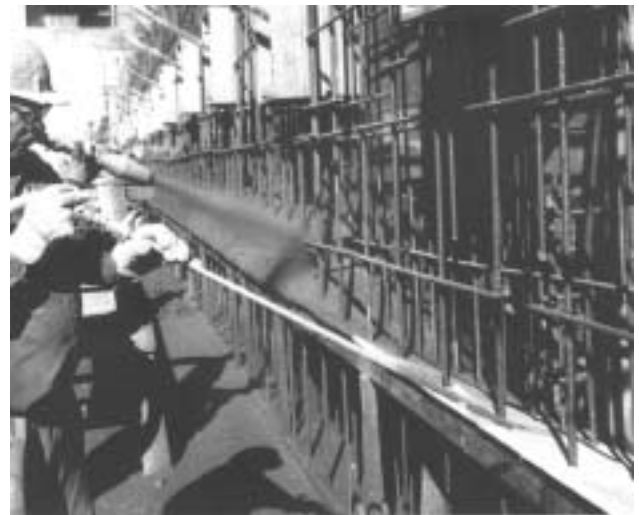


Fig. 8.6—Blowpipe operator cleaning overspray and rebound in advance of the nozzle operator.

The method of encasing two or more layers of vertical reinforcement depends on the method of shooting a vertical wall.

When shooting walls in vertical layers, delay placement of successive layers of reinforcement until the previous layer is encased, thus avoiding having to shoot through more than one layer of reinforcement. When bench shooting, place all the reinforcement before shooting. The layer of reinforcement next to the nozzle should have a minimum spacing of 12 bar diameters in both directions, and the back layer a minimum spacing of six bar diameters in both directions (Section 8.5.8). When shooting through two layers of steel, a blowpipe operator should remove rebound and overspray.



Fig. 8.7—Dry-mix shooting final coat of 1 to 1-1/2 in. (25 to 38 mm) of shotcrete to previously gunned wet shotcrete base.



Fig. 8.8—Dry-mix shotcrete pilaster between two concrete tilt-up panels.

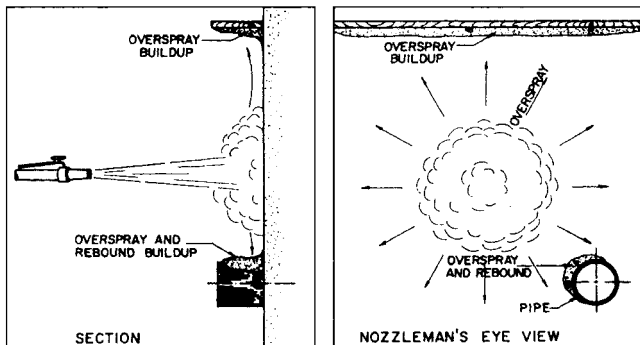


Fig. 8.9—Overspray and rebound.

When a project requires placement through a complex section of reinforcement, a preconstruction test panel should be made, shot, and cut up to determine if the reinforcement can be adequately encased. The panel should be cut or cored through the reinforcement where the greatest congestion occurs. It is not advisable to apply shotcrete into narrow slots, holes, or spirally reinforced columns or piling (Litvin and Shideler 1964).

8.5.11 Rebound and overspray—Rebound and overspray are two of the unwanted by-products of shotcreting, as shown in Fig. 8.9.



Fig. 8.10—Overspray on reinforcing bars at the top of a band of shotcrete.

Both can be somewhat controlled or minimized by a nozzle operator with proper expertise. Overspray is light material carried away from the receiving surface and has similar characteristics in both the wet-mix and dry-mix processes. It adheres to ground wire, shooting strips, forms, reinforcing steel, and other projections, leaving an unconsolidated thickness of low-quality shotcrete (Fig. 8.10).

Overspray should be removed, preferably before it hardens. If left in place and covered with fresh shotcrete, it may cover hollows and sand pockets and reduce bond.

Rebound is aggregate and cement paste that ricochets off the surface during the application of shotcrete because of collision with the hard surface, reinforcement, or with the aggregate particles themselves. The amount of rebound varies with the position of the work, nozzle angle, air pressure, impact velocity, cement content, water content, maximum size and gradation of aggregate, amount of reinforcement, and thickness of layer. A blowpipe is sometimes used to remove and control rebound.

Initially the percentage of rebound is large, but it becomes less after a plastic cushion of shotcrete has built up. Rebound is much leaner and coarser than the original mixture. The cement content of the in-place shotcrete is, therefore, higher because of rebound; this increases the in-place shotcrete strength, but also increases drying shrinkage.

Rebound should not be incorporated into the construction. A blowpipe operator should remove rebound that does not fall clear of the work. Rebound should not be salvaged and included in later batches because of the danger of contamination and poor quality. Also, the cement content, state of hydration, and grading of the aggregate are all variable and unpredictable. **Table 8.1** shows approximate rebound losses for dry-mix and wet-mix shotcrete.

Rebound losses may be higher or lower depending on the expertise of the individual nozzle operator and the factors mentioned previously.

Table 8.1—Approximate range of rebound losses

Surface	Percent of rebound
Floor or slabs	0 to 10
Sloping and vertical walls	10 to 30
Overhead work	10 to 30

8.5.12 Suspension of work—Shooting should be suspended under the following inclement weather conditions (Sections 8.8 and 8.10):

- High winds preventing proper application procedures;
- Temperature approaches freezing and the work cannot be protected; and
- Rain causing washouts or sloughing of the fresh shotcrete.

8.5.13 Access and visibility—The nozzle operator should have clear access and clear visibility from a safe, stable work platform. Move utilities or other obstructions before placing shotcrete to provide clear access. Platforms and scaffolding should meet all applicable safety standards. Appropriate lighting should be provided when necessary to provide the nozzle operator with a clear view of the work.

8.6—Finishing

Unlike concrete, shotcrete has little excess water to provide the particle lubrication necessary for effective finishing. Careful finishing by experienced skilled craftsmen, however, can provide a high-quality finish. Finishing of wet-mix shotcrete follows the same procedures as dry-mix, except that finishing may be somewhat easier for wet-mix due to the higher water content.

8.6.1 Natural finishes—The gun finish is the natural finish left by the nozzle after the shotcrete is brought to approximate line and grade. It leaves a textured, uneven surface that is suitable for many applications. In cases where better alignment, appearance, or smoothness are required, the shotcrete is placed a fraction beyond the guide strips, ground wires, or forms. It stiffens to the point where the surface will not pull or crack when screeded with a rod or trowel. Excess material is then trimmed, sliced, or scraped to true line and grade (Fig. 8.11). If subsequent layers of shotcrete are to be placed over the surface, the surface should be prepared by removing surface laitance either by brooming or screeding, etching, scraping, waterblasting, sandblasting, or other acceptable methods.

In dry-mix shotcrete, the natural or gun finish is a good finish from both a structural and durability standpoint. If further finishing is required, the finisher should be careful not to disturb the section, create cracks, reduce internal cohesion, or break bond between the shotcrete and the reinforcement or shotcrete and the underlying material. With dry-mix shotcrete, additional finishing may not be easily accomplished because it is usually stiff and difficult to work under normal trowel manipulation.

The guide strips or ground wires are then removed, and the impressions they leave are removed by floating. The finish left in this condition is a natural rod finish. If this finish is broomed, it is called a natural broom finish. It may also be given a float or steel trowel finish as described in Section 8.6.3.

8.6.2 Flash and finish coats—Where a finer finish or better appearance is desired, a flash coat may be used. The flash coat



Fig. 8.11—Screeding excess or overgunned shotcrete, leaving a rough, textured finish.

is a thin surface coating up to 1/4 in. (6 mm) thick. The flash coat is applied to the shotcrete surface that was left about 1/4 in. (6 mm) low, either immediately after screeding or at a later time, and is finished as described in Section 8.6.1.

For thick walls, an alternate approach is to apply a finish coat, which can provide greater uniformity in texture and appearance. The basic shotcrete application is brought to within 1/4 to 1 in. (5 to 25 mm) of the final grade. A thin surface or finish coat, 1/4 to 1 in. (5 to 25 mm), may be applied immediately after screeding or at a later time. If the finish coat is applied later, the base shotcrete should be left properly scarified or broomed. Just before the application of the final or finish coat, the finisher should wash the receiving surface with an air-water blast. The finish coat may use sand similar to that used in the base coat.

8.6.3 Final finishes—The flash or finish coat may be finished in one of the following ways:

- **Wood float**—This procedure leaves a uniform but granular texture. It is also used as a preliminary finish for other surface treatments;
- **Rubber float**—A sponge rubber float is applied directly to the flash coat or wood float finish, leaving a somewhat finer finish;
- **Brush**—A fine hairbrush float finish gives a finely textured, sandy finish; and
- **Steel trowel**—A steel trowel finish is applied to a wood float finish, leaving a smooth, hard finish. This finish is difficult to achieve and requires considerable effort. Most shotcrete finishes are more coarsely textured than their concrete counterparts (Fig. 8.12(a) and (b)).

If a plaster coat is to be applied later, the finished shotcrete should be left open-textured after trimming, slicing, or screeding, to ensure bond. Smooth areas should be properly scarified or broomed.

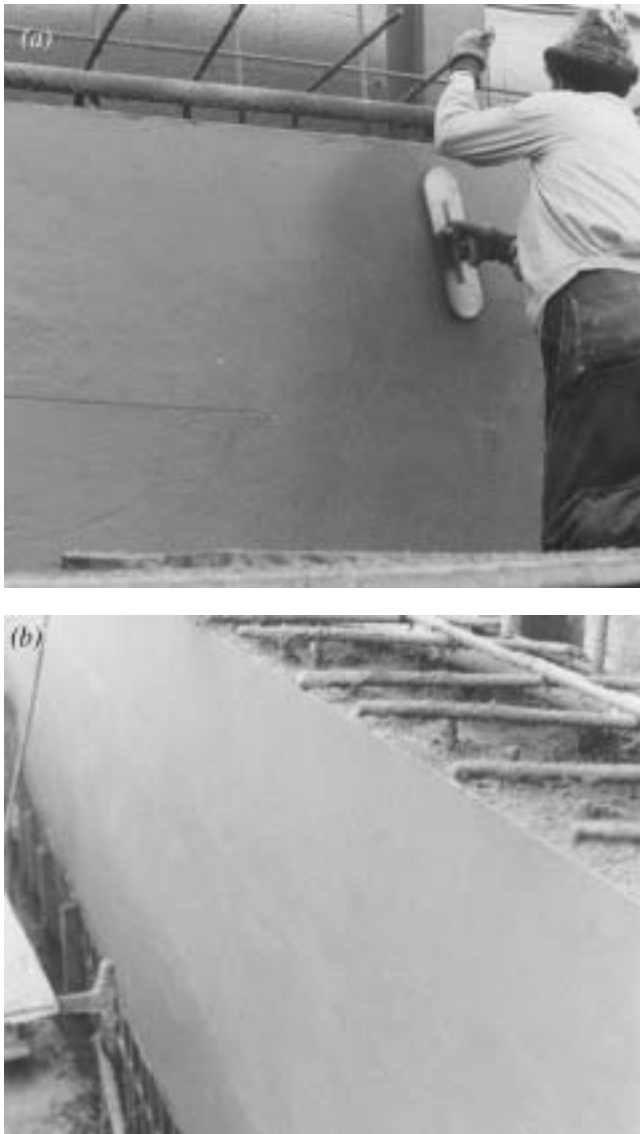


Fig. 8.12—(a) Applying a steel trowel finish to freshly gunned shotcrete finish; and (b) final finish appearance.

8.7—Tolerances

Tolerances should be based on use and function. Typically, shotcrete structures are not required to meet the tolerance standards of cast-in-place concrete. Tolerance requirements for many shotcrete applications, such as underground support, below-grade walls, and slope stabilization, may vary as much as 4 in. (100 mm). If needed, shotcrete can be finished to tight tolerances. Some of the economy that shotcrete placement brings to a project, however, may be lost if tight tolerances are specified.

8.8—Curing

Shotcrete, like concrete, should be properly cured so that its potential strength and durability are fully developed. This is particularly true for the thin sections and low w/cm associated with shotcrete. The best method for curing is to keep the shotcrete wet continuously for 7 days while maintaining a temperature over 40 °F (5 °C). The temperature of the curing water should not be lower than 20 °F (10 °C) cooler than the

shotcrete surface at the time the water and shotcrete come in contact. Covering shotcrete with sheet materials (ASTM C 171) is another method used to cure shotcrete.

Curing compounds are satisfactory if drying conditions are not severe, no additional shotcrete or paint is to be applied, and the resulting appearance is acceptable. Where the surface has a natural gun or flash finish, the liquid membrane-curing compound (ASTM C 1315) should be applied at a rate twice that recommended by the compound manufacturer. A fugitive dye is helpful to monitor coverage. Natural curing may be allowed if the relative humidity is continuously maintained at or above 85%. More detailed information on curing can be found in ACI 308.1 and ACI 506.2. The crew should avoid rapid drying of shotcrete at the end of the curing period.

8.9—Hot-weather shotcreting

With dry-mix shotcrete, the time from mixing to shooting a mixture should not exceed 15 minutes; otherwise, undesirable decreases in strength due to prehydration can occur.

With wet-mix shotcrete, the undesirable effects are similar to those encountered with normal pumped concrete. The problems include increased water demand, increased rate of slump loss, increased rate of set, and difficulty in regulating entrained air content. There should be procedures to handle these problems to ensure a satisfactory shotcrete installation.

Once the shotcrete is in place, placing, finishing and curing procedures are similar to those for concrete. Screeding and finishing operations should proceed as rapidly as the shotcrete conditions allow. Curing should start promptly after finishing is completed. Ideally, the temperature of the shotcrete should be maintained between 50 and 100 °F (10 and 38 °C) during all phases of the installation procedure. ACI 305R should be referred to for more detailed information.

8.10—Cold-weather shotcreting

The shotcreter should not place shotcrete on frozen surfaces. This and other precautions used to protect concrete from freezing should also be used for protecting shotcrete. Shotcrete has a greater heat of hydration than conventional cast-in-place concrete because of its higher cement factor that aids in resisting freezing, but it is placed in thin layers with large surface areas providing for rapid loss of heat that partially counter-balances the heat of hydration benefits. Shooting can be allowed if the temperature is at least 40 °F (5 °C) and rising and discontinued at 40 °F (5 °C) and falling. At low temperatures, however, strengths will develop slowly until higher temperatures are restored. Low temperatures will reduce the rate of hydration and may inhibit setting and early-strength development.

Once the shotcrete is in place and finished, it should be cured and protected from freezing until it reaches sufficient strength. Water curing in a freezing environment is not recommended. The temperature during curing should be maintained above 40 °F (5 °C). When shotcrete will be placed under cold-weather conditions, a plan should be developed outlining procedures for surface preparation, shotcrete placement, curing, and protection. Shotcrete can be

placed successfully under adverse conditions with proper planning and procedures designed for the specific application. Refer to ACI 306R for more information on all aspects of cold-weather concreting.

8.11—Hazards

A shotcrete operation has multiple hazards. In addition to operating equipment, shotcrete operations have hazardous high-pressure lines (air, water, and material). Pressurized air-lines are particularly hazardous. Rebound can be projected in all directions. All personnel in the vicinity of the nozzle operation should wear proper eye protection, and rebound should be prevented from harming the passing public or adjacent property.

Shotcreting is physically demanding and should not be undertaken by anyone with physical limitations. Material hoses are heavy and difficult to drag. Safe scaffolding should be provided and maintained to provide adequate and safe access to the work.

Some personnel may be affected by cement, which can cause dry and cracked skin, dermatitis, and alkali burns. Admixtures, particularly caustic accelerators, and special proprietary mixtures may create additional hazards. Personnel should use proper protective devices, ointments, and clothing, and exercise caution in enclosed areas. Where dust, mist, or other airborne particulate matter is a problem during shotcreting, personnel should employ respirators or dust masks and make special provisions for ventilating the work area.

The use of fibers in shotcrete can produce problems for personnel during shotcreting and finishing operations. The nozzle operator and any helpers should have complete face and eye protection and clothes that cover all skin areas. Craftsmen should be aware that fibers can collect in clothing. Protruding fibers in the shotcrete surface can pose a hazard to the finisher or rodman. A flash coat of non-fibrous shotcrete can eliminate this problem.

CHAPTER 9—QUALITY CONTROL

9.1—Introduction

Shotcrete is a unique method of placing concrete with many unusual applications that require careful attention to details from design through construction. Therefore, it is essential that quality-control procedures be established 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.

The size and character of the application usually determines the amount of effort that should be expended on quality control. The cost should be equated with the benefits to be derived. Quality control not only includes testing procedures but also constant monitoring of every phase of the shotcrete installation. Implementing a quality-control program for a shotcrete installation requires an enlightened approach. Whoever is entrusted with this task should have an understanding of and experience in the application of shotcrete and have sufficient flexibility to adapt the specifications to specific

field conditions. Reference standards may be found in **Chapter 10**. ACI 506.2 should be used as the basis for the quality control procedures. ACI 121R and ACI 311.4R contain valuable guidance on the establishment of quality programs.

9.2—Design and quality control

Proper design is an 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.

9.3—Materials

The source of all materials should be submitted to the design authority for approval. If the source is approved, the material should either be certified by the supplier that it meets specifications or be tested on a regular basis. The project size and character would dictate which procedure is suitable. Mixture proportions may be detailed in the specification or may be selected by the contractor to produce a specified compressive strength or other properties. In either case, a design or proof mixture must be made and tested. Delivery, handling, and storage of the materials should be checked for compliance with the specifications. For supplemental information on specific details for quality control of shotcrete materials, refer to ACI 506.2 and **Chapter 2** of this guide.

9.4—Application equipment

Chapter 3 has a comprehensive description of equipment that can help achieve the desired result. Air requirements, both pressure and volume, should be monitored on a regular basis. Compressors, shooting equipment, mixers and batchers, and hoses should be properly maintained, cleaned, calibrated, and checked regularly for proper function.

9.5—Craftsmanship

Chapter 4 outlines criteria for personnel qualification. Only competent craftsmanship will produce high-quality shotcrete. There are two basic procedures to help ensure the desired craftsmanship: applicator evaluation and preconstruction testing. ACI CP-60 provides a method for the certification of shotcrete nozzle operators. Job specifications should include the requirements for this certification.

The applicator should have a traceable history of completed, acceptable, quality shotcrete work similar to that required for the project. The principals and shotcrete crew should have a successful background in this field, as determined by reference and reputation. Supporting technical or testing data should supplement any literature or information submitted by the applicator. Requiring prequalification helps expedite the evaluation procedure.

Preconstruction testing procedures using the personnel, materials, and equipment to be used on the project are outlined in ACI 506.2. Tests should be conducted under similar conditions expected to be experienced in the actual application.

9.6—Placement techniques

One of the most important factors that should be considered in shotcrete installation is placement technique. If quality control is excellent in all other aspects of the shotcrete application but placement is questionable, an unsatisfactory product may result. The procedures and techniques described in other portions of this guide should be followed closely because they represent good shotcrete practice.

9.7—Inspection

A knowledgeable, thorough, and qualified inspector is a necessary requirement for implementing quality-assurance procedures. The inspector should be familiar with plans, specifications, and applicable standards. The inspector should understand all facets of the shotcrete process, especially the installation technique referred to in [Chapter 8](#). The inspector should continuously inspect the work, paying attention to materials, forms, reinforcement, equipment, placement, finishing, curing, and protection of the finished product. The inspector also is responsible for the field-testing as outlined in the following section.

9.8—Testing procedures

An important aspect of quality assurance is the physical testing of the shotcrete before, during, and after placement. ACI 506.2 describes the procedures to be followed in preconstruction and construction testing. The agency providing the testing and/or inspection should meet the requirements of ASTM E 329.

Normal testing ages for compressive strength are 7 and 28 days; however, shorter periods may be required for particular applications or conditions. Testing 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 and complexity of the project. Sampling should be done in accordance with ASTM C 1385. Making extra cylinders or panels is sometimes done if testing results vary.

Other testing may include tests for water absorption, drying shrinkage, and resistance to freezing-and-thawing cycles. Fiber-reinforced shotcrete may require fiber washout tests or flexural toughness testing according to ASTM C 1018.

Acceptance of shotcrete should be based on results obtained from drilled cores or sawed cubes (ASTM C 42). The use of data from nondestructive testing devices, such as impact hammers or probes (ASTM C 805, ASTM C 803), ultrasonic equipment (ASTM C 597), and pull-out devices (ASTM C 900) 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. Refer to ACI 228.2R for additional information on nondestructive testing.

Core grading is a method used to evaluate encasement of reinforcement. Core grading is only used for nozzle operator evaluation and is done in accordance with ACI CP-60. Core grading should not be used to evaluate structures.

CHAPTER 10—REFERENCES

10.1—Referenced standards and reports

The standards and reports listed as follows were the latest editions at the time this document was prepared. Because

these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute

121R	Quality Management System for Concrete Construction
211.1	Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
214R	Evaluation of Strength Test Results of Concrete
228.2R	Nondestructive Test Methods for Evaluation of Concrete in Structures
301	Specifications for Structural Concrete
304R	Guide for Measuring, Mixing, Transporting, and Placing Concrete
304.2R	Placing Concrete by Pumping Methods
304.6R	Guide for the Use of Volumetric-Measuring and Continuous-Mixing Concrete Equipment
305R	Hot Weather Concreting
306R	Cold Weather Concreting
308R	Guide to Curing Concrete
308.1	Standard Specification for Curing Concrete
311.4R	Guide for Concrete Inspection
318	Building Code Requirements for Structural Concrete
506.1R	Committee Report on Fiber Reinforced Shotcrete
506.2	Specification for Shotcrete
506.4R	Guide for the Evaluation of Shotcrete
546R	Concrete Repair Guide
547R	Refractory Concrete: State-of-the-Art Report
CP-60	Craftsman Workbook for ACI Certification of Shotcrete Nozzleman
SP-57	Refractory Concrete

ASTM International

A 185	Standard Specification for Steel Welded Wire Reinforcement, Plain, for Concrete
A 497	Standard Specification for Steel Welded Wire Reinforcement, Deformed, for Concrete
A 820	Specifications for Steel Fibers for Fiber-Reinforced Concrete
C 33	Standard Specification for Concrete Aggregates
C 42	Standard Test Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 94	Standard Specification for Ready-Mixed Concrete
C 150	Standard Specification for Portland Cement
C 157	Standard Test Method for Length Change of Hardened Hydraulic-Cement, Mortar, and Concrete
C 171	Standard Specification for Sheet Materials for Curing Concrete
C 173	Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
C 231	Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
C 260	Standard Specification for Air-Entraining Admixtures for Concrete

- C 309 Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete
- C 330 Standard Specification for Lightweight Aggregates for Structural Concrete
- C 457 Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete
- C 595 Standard Specification for Blended Hydraulic Cements
- C 597 Standard Test Method for Pulse Velocity Through Concrete
- C 618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolans for Use in Concrete
- C 642 Standard Test Method for Density, Absorption, and Voids in Hardened Concrete
- C 666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
- C 672 Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
- C 685 Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing
- C 803 Standard Test Method for Penetration Resistance of Hardened Concrete
- C 805 Standard Test Method for Rebound Number of Hardened Concrete
- C 900 Standard Test Method for Pullout Strength of Hardened Concrete
- C 989 Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars
- C 1018 Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)
- C 1116 Standard Specification for Fiber-Reinforced Concrete and Shotcrete
- C 1140 Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels
- C 1141 Standard Specification for Admixtures for Shotcrete
- C 1157 Standard Performance Specification for Hydraulic Cement
- C 1218 Standard Test Method for Water-Soluble Chloride in Mortar and Concrete
- C 1240 Standard Specification for Silica Fume Used in Cementitious Mixtures
- C 1315 Standard Specification for Liquid Membrane-Forming Compounds Having Special Properties for Curing and Sealing Concrete
- C 1385 Standard Practice for Sampling Materials for Shotcrete
- C 1398 Standard Test Method for Laboratory Determination of the Time of Setting of Hydraulic-Cement Mortars Containing Additives for Shotcrete by the Use of Gillmore Needles
- C 1436 Standard Specification for Materials for Shotcrete

- C 1480 Standard Specification for Packaged, Pre-Blended, Dry, Combined Materials for Use in Wet and Dry Shotcrete Application
- E 329 Standard Specification for Agencies Engaged in the Testing and/or Inspection of Materials Used in Construction

International Concrete Repair Institute

- 03737 Guide for the Preparation of Concrete Surfaces for Repair Using Hydrodemolition Methods

The Society for Protective Coatings

- SSPC SP6/ Commercial Blast Cleaning, Steel Structures
- NACE No. 3 Painting Manual, V. 2, 2000
- SSPC SP13/ Surface Preparation of Concrete, 1997
- NACE No. 6

U.S. Environmental Protection Agency

- EPA Small Entity Compliance Guide, "National Volatile Organic Compound Emission Standards for Architectural Coatings," *EPA-453/R-99-003*, July 1999

The above publications may be obtained from the following organizations:

American Concrete Institute
PO Box 9094
Farmington Hills, MI 48333-9094

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428

International Concrete Repair Institute
3166 South River Rd., Ste 132
Des Plaines, IL 60018

The Society for Protective Coatings
40 24th St., Sixth Floor
Pittsburgh, PA 15222-4656

U.S. Environmental Protection Agency
National Service Center for Environmental Publications
PO Box 42419
Cincinnati, OH 45242

10.2—Cited references

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ACI Committee 506, 1966, *Shotcreting*, SP-14, American Concrete Institute, Farmington Hills, Mich., 224 pp.

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APPENDIX—PAYMENT FOR SHOTCRETE WORK

A.1—Introduction

Many factors should be considered when establishing the best method for payment for shotcrete work. There is no universal pay item that will fit every situation, but a proper specification is mandatory if both owner and applicator are to receive fair treatment. All factors (Section A.3) peculiar to a specific project should be reviewed and considered. Once a factor analysis is complete, a determination should be made as to which of the work requirements or preliminary procedures, other than those directly associated with the shotcrete placement, should be included in the shotcrete pay item. The work items that should be considered are: surface preparation, formwork, anchorage-support and spacers, reinforcement, quality control, and coating (painting) if required. Alignment control, joints, and protection of adjacent surfaces are usually included in the shotcrete item.

The method of measurement should be specified to eliminate any ambiguities as to the items included or excluded from the method for payment. If the items are not to be measured, it should so state in the specifications.

A.2—Payment methods

Payment for shotcrete work is made on one or more of the methods shown in [Table A.1](#), or a combination thereof, depending on the nature and scope of the project.

A.3—Factors affecting payment

Where the area and depth of the shotcrete application are fixed and the other job parameters are known, specified, or can be inspected in place without difficulty, a lump sum basis for payment is recommended. Most projects, however, are not that simple in concept or execution, and factors in Sections A.3.1 through [A.3.10](#) should be considered when establishing a method for payment.

A.3.1 Geometry or work configuration—To a great extent, the shape of the area to be shotcreted will determine the best method for payment. If the area and depth are uniform, a Class A method is dictated. If either area or depth is not uniform and cannot be measured easily, then a Class B or C method of payment is recommended.

A.3.2 Job conditions—Certain projects have working conditions that make them difficult to estimate, such as limited access and work areas, security problems, possible periods of delay, or a combination thereof. In these cases, a Class B method would be most suitable.

A.3.3 Scope of work—Occasionally, several types of shotcrete work exist on the same project. If this occurs, then the proper method for payment should be ascribed to each

type of work. Also, consideration should be given to the fact that changes may be required during construction and these provisions should be included in the original proposal or contract to cover such possibilities.

A.3.4 Latent conditions—Where the extent of work is unknown and cannot be properly evaluated so that latent conditions may exist, or the project is so complex that unknown problems are anticipated, it is advisable to use a Class B method for payment.

A.3.5 Measurement capability—For many shotcrete applications, accurate measurement may be possible, but access is difficult or the areas of measurement may be small and widespread. In other cases, frequent measurements of the dimensions may have to be made to obtain accurate quantities. Under these circumstances, an inspector would have to be available on short notice to avoid delays to the contractor, whether the measurements are made before or after shotcreting.

A.3.6 Owner's production schedule—Many shotcrete projects are accomplished while the owner maintains plant operations. This situation creates very exacting working conditions for the contractor, which in turn makes firm quotation almost impossible. If this is the case, a Class B method of payment would be the best alternative.

A.3.7 Owner's payment policy—Many federal, state, and municipal projects are required to be bid using a Class A method. Problems can develop when the work is not suited to this method of payment. It behooves the specifying agency to eliminate all possible areas of contention by providing a concise specification and detailed scope of work.

A.3.8 Clarity of specification—All the elements that will aid in providing a well-executed and satisfactory shotcrete job should be written into the specification. Type of process (wet-mix or dry-mix), materials, design mixture, admixtures, quality and method of preparation, anchorage and reinforcement details, construction joints, finish, curing procedure, and testing requirements all should be explicitly detailed. If a performance specification is to be used, it should be presented with realistic goals. The specification should be clear as to which items are and which are not included in the shotcrete pay item. This is extremely important in Class A and C methods for payment.

A.3.9 Variety of operations—There are times when the shotcreting portion of the work is of a minor nature compared to the preparation, anchorage, reinforcement, or other items. It would be impractical to include these items in the shotcrete pay item. To properly balance the proposal, it should be determined whether the shotcrete item should be included in another item or that all the involved items be listed separately.

A.3.10 Competency of contractor—There are geographical areas where the shotcrete contractors available may not have the expertise or experience required for a particular application. To avoid the possibility of excessive cost or inferior results from unrealistically low prices, consider using the Class B method of payment with a prequalified applicator.

Table A.1—Payment methods for shotcrete*

Class A	Class B	Class C
1. Lump sum	1. Per diem	1. Bag of cement [†]
2. Area (square units)	2. Time and material	2. Volume conversion [‡]
3. Volume (cubic units)	3. Cost plus fixed fee	3. Cubic yard of wet-mix shotcrete
4. Lineal feet (of tunnel, canal, and pipe)		

*Refer to Section A.5 for definition of classes.

[†]Refer to Section A.5.3.1.

[‡]Refer to Section A.5.3.2.

A.4—Supplementary items

In most cases, surface preparation, formwork, anchorage, reinforcement, quality control, and coating are included in the shotcrete pay item. There are instances, however, when it is advisable to set up separate pay items for one or more of these items.

A.4.1 Surface preparation—This item usually includes preparation of one or more of the following: concrete, steel, wood, rock, and earth. Usually these items are compatible with the shotcrete pay item, especially when they are small in quantity. Where the volume of work is large, however, rock and earth excavation should be listed separately.

A.4.2 Formwork—This item of work is not usually of major proportions of a shotcrete project except in new construction; however, when it is, it should be listed separately as a pay item.

A.4.3 Anchorage—The installation of anchors for reinforcement support, spacing, or both, is almost always included with the shotcrete item, but may be included with the reinforcement when the latter is a separate pay item.

A.4.4 Reinforcement—This item consists of welded-wire reinforcement, reinforcing bars, or special anchors and usually is included in the shotcrete pay item.

A.4.5 Quality control—The cost attendant to quality control can be high in proportion to the project size. The specifications should clearly explain the responsibility of each participant with regard to this item. In any case, this item should not be included in the shotcrete pay item. The owner should arrange and cover costs for quality control tests.

A.4.6 Shotcrete coating—Where shotcrete is to be coated with a liquid material, such as paint, epoxy, or linseed oil, payment should be on a separate item and not included in the shotcrete pay item.

A.4.7 Special materials—Unless there is some special reason to do otherwise, admixtures, fibers, and other additives should be included in the shotcrete pay item.

A.5—Methods of measurement

The method of measurement specified for the project should consider the nature of the project, the physical difficulties of measurement, owner's and contractor's responsibilities for measurement, and the desired accuracy of the quantities. Measurements should be made in a manner that will ensure accuracy without interfering with job progress. No measurements are taken on a lump sum project, unless extra

work is ordered by the owner. Measurements can be classified according to whether they are direct, indirect, or cost plus.

A.5.1 Direct method (Class A)—These are methods where dimensions are physically measured in the field. These types of measurement and lump sum projects usually provide the fairest and most equitable basis for payment. In the case of direct measurement where variable cross sections or depths occur, the technique for measurement should be specified as being before or after the shotcrete application. Additions or deductions for overlaps, chamfers, filets, rivet heads, openings, or minor ornamentation are usually not made unless their size justifies a measurement and it is so specified.

A.5.2 Cost plus (Class B)—Cost-plus methods are used primarily where the scope and extent of the work cannot be determined before the start of work. If properly administered, they can result in lower costs to the owner because they eliminate risk on the part of the contractor. They require a competent, trustworthy contractor in whom the owner has complete confidence.

A.5.3 Indirect method (Class C)

A.5.3.1 Bag method—Indirect methods, such as bags of cement used in the mixture, cubic yards of wet-mix shotcrete, and volume conversion, are less desirable than the direct methods and can lead to abuses if not properly administered. If used, they should be adequately supervised.

Measurement for shotcrete payment on a bag of cement used basis requires careful checking of cement deliveries and counting bags used on a frequent and not-less-than-daily basis. Attention should also be paid to proper proportioning and minimizing waste from rebound. Only material that passes through the gun is measured.

Measurement for shotcrete payment on a basis of a cubic yard of wet-mix shotcrete delivered through a concrete pump requires daily monitoring of transit-mixed concrete truck delivery tickets. Only material passing through the pump is measured.

A.5.3.2 Volume conversion—The volume conversion method uses the volume of materials used in the mixture, usually the volume of cement, multiplied by a specified conversion factor that will result in the approximate volume of material in place. Attention should be given to proportioning and rebound waste, because all material that passes through the gun is considered.

A.6—Pay items

A.6.1 Class A

A.6.1.1 Lump sum—The parameters of the project are fixed with a lump sum payment, and the price includes full compensation for bond, mobilization and demobilization, equipment, and all incidentals necessary to complete the work as specified. This includes surface preparation;

anchorage; furring; reinforcement; shotcrete application, including all materials; finishing; curing; and replacement of defective material.

A.6.1.2 Area—An area and depth are specified, and payment is based on the completed area in square given units. The price usually includes full compensation for the same items and work as listed under Section A.6.1.1.

A.6.1.3 Volume—This section is similar to Section A.6.1.2, except that the volume in cubic units is specified. The same basic conditions exist as for Section A.6.1.1.

A.6.2 Class B

A.6.2.1 Per diem—Payment is based on prices bid or supplied for:

- Mobilization and demobilization, straight and overtime rates for specified types and quantities of labor and equipment, and prices for required materials; and
- Cost of additional labor of each type included as supplemental pay items; the prices include all the items covered in Section A.6.1.1.

A.6.2.2 Time and materials—Payment is based on prices bid or supplied for:

- Hourly or per diem wages for each classification of labor, cost of insurance, unemployment taxes, worker's compensation, fringe benefits, hourly or per diem rates for required equipment, rates for material including transportation and taxes, and percentages for profit and overhead; and
- Time sheets, including labor hours, equipment, and material charges approved daily; they should be supplemented by properly certified documents to cover all charges for the work performed.

A.6.2.3 Cost plus fee—Payment is handled as in Section A.6.2.2, except that the size of the project or other factors require the fee for overhead and profit be a lump sum or graduated according to the final size of the project.

A.6.3 Class C

A.6.3.1 Bag cement—Payment using this item is based on the number of bags of cement used in the project. The price again includes full compensation for all the items listed in Section A.6.1.1.

A.6.3.2 Volume conversion—Payment using this item is essentially the same as in Section A.6.3.1, except that the measurement may be different and the price is based on cubic units.

For wet-mix shotcrete, payment using this item is based on number of cubic yards of wet-mix shotcrete delivered through a concrete pump and used on the project. The unit price per cubic yard includes full compensation for all the items listed in Section A.6.1.1.