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Guide to Shotcrete

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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. Preconstruction, prequalifying, and acceptance testing of workers, materials, and finished shotcrete are also considered.

Keywords: concrete construction; concrete finishing (fresh concrete); equipment; mix proportioning; mortars (material); placing; quality control; shotcrete.

CONTENTS

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ACI 506R-85 replaces ACI 506-66 (Revised 1983) which was withdrawn as an ACI standardin 1983 The 1990 rev ision updates the references

CHAPTER l-GENERAL

1.1-Introduction

The shotcrete process has grown into an important and widely used construction technique. Because of continued developments in materials, equipment, and construction procedures in recent years, this guide was prepared to replace "Recommended Practice for Shotcreting (ACI 506-66)" (Revised 1983).

1.2-Objectives

This guide covers many aspects of shotcrete construction including materials, equipment, crew organization, preliminary preparation, proportioning, shotcrete placement, and quality control. An appendix on suggested methods of payment is also included. New construction, repair, linings, coatings, refractories, underground support, and other special applications are discussed. No attempt is made to provide guidelines for the design of shotcrete installations. The techniques and procedures described herein are based on many years of practice and experience. However, procedures vary from one region to another, and adjustments may be required to meet the needs of the particular project.

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 of this device was given the proprietary name Gunite. In the ensuing years, trademarks such as Guncrete, Pneucrete, Blastcrete, Blocrete, Jetcrete, and the terms pneumatically applied mortar and 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 Gunite process. In 1951, the American Concrete Institute adopted the term shotcrete to describe the dry-mix process. It is now also applied to the wet-mix process and has gained universal acceptance in the United States.

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. These innovations enhanced the utility, flexibility, and general effectiveness of the process.

1.4-Reference standards

The standards and specifications referred to in this guide are listed in Chapter 10 with their complete designation and title including the year of adoption or revision.

1.5-Definitions

The following definitions cover terms used in shotcreting:

Air ring-Perforated manifold in 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 next layer of shotcrete.

Alignment wire-See Ground wire.

Blowpipe-Air jet operated by nozzleman's helper in shotcrete gunning to assist in keeping rebound or other loose material out of the work.

Board butt joint-Shotcrete construction joint formed by sloping gunned surface to a l-in. board laid flat on receiving surface.

Buildup-Thickness of shotcrete.

Bulking-Increase in volume of sand in a moist condition over the same quantity dry.

Conveying hose-See Delivery hose.

Cutting screed-Sharp edged tool used to trim shotcrete to finish outline. See Rod.

Delivery equipment-Equipment which introduces shotcrete material into the delivery hose.

Delivery hose-Hose through which shotcrete materials pass on their way to 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. See Pneumatic feed.

Feed Wheel-Material distributor or regulator in certain types of shotcrete delivery equipment.

Finish coat-Final thin coat of shotcrete preparatory to hand finishing. See Flash coat.

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

Gun-Shotcrete delivery equipment.

Gun casting-Placing concrete or mortar using a special velocity reducing casting head and standard shotcrete delivery equipment.

Gun finish-Undisturbed final layer of shotcrete as applied from nozzle, without hand finishing.

Gunite-Term sometimes used for dry-mix shotcrete.

Gunman-Worker on shotcreting crew who operates delivery equipment; also known as Gun operator.

Gunning-Act of applying shotcrete; shotcreting.

Gun operator-See Gunman.

Hamm tip-Flared shotcrete nozzle having a larger diameter at midpoint than either inlet or outlet; also called Premixing tip.

Hydro nozzle-A special prewetting and mixing nozzle consisting of a short length of delivery hose inserted between the nozzle body and nozzle tip.

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 which has a regulating valve and contains a manifold (water or air ring) to introduce water or air to 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 prevent wear.

Nozzleman-Worker on shotcrete crew who manipulates the nozzle, controls consistency with the dry process, and controls final disposition of the material.

Nozzle velocity-Velocity of shotcrete material particles at exit from nozzle, in feet per second (meters per second).

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.

Pneumatically applied concrete-See Shotcrete.

Pneumatically applied mortar-See Shotcrete.

Pneumatic feed-Shotcrete delivery equipment in which material is conveyed by a pressurized air stream.

Positive displacement-Wet-mix shotcrete delivery equipment in which the material is pumped through the delivery hose in a solid mass by a pump or other non-pneumatic means. Air is introduced into the material flow at the nozzle.

Predampening-In the dry-mix process the addition of water to the aggregate prior to mixing to bring its moisture content to a specified amount, usually 3-6 percent.

Prewetting-In the dry-mix process the addition of a portion of mixing water to shotcrete materials in the delivery hose at some distance prior to the nozzle.

Puddling-Placement of shotcrete wherein air pressure is decreased and water content is increased, usually an undesirable method of shotcreting.

Pump-Wet-mix delivery equipment.

Pump operator-Workman on wet-mix shotcreting crew who operates delivery equipment.

Rebound-Shotcrete material leaner than the original mixture which ricochets off the receiving surface and falls to the ground.

Rod-Sharp-edged cutting screed used to trim shotcrete to forms or ground wires.

Rolling-Result of applying shotcrete at angles less than 90 deg to the receiving surface resulting in an uneven, wavy, textured surface at the outer edge of spray pattern.

Sagging-See Sloughing.

Sand pocket-A zone in the shotcrete containing fine aggregate with little or no cement.

Screed wire-See Ground wire.

Shooting-Act of applying shotcrete; see Gunning.

Shotcrete-Mortar or concrete pneumatically projected at high velocity onto a surface.

Sloughing-Subsidence of shotcrete, due generally to excessive water in mixture; also called Sagging.

Slugging-Pulsating or intermittent flow of shotcrete material.

Water ring-A device in the nozzle body of dry-mix shotcrete equipment through which water is added to the materials.

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. If accelerator is used it is normally added at the nozzle.

Wetting-In the dry-mix process, the addition of mixing water to shotcrete materials just prior to exit from the nozzle.

1.6-Shotcreting processes

Shotcreting is usually classified according to the process used, wet-mix or dry-mix, and the type of aggregate used, coarse or fine. See Table 2.1 for fine aggregate gradation No. 1, and coarse aggregate gradations No. 2 and No. 3.

1.6.1 *Dry-mix process*-This process consists of the following steps:

(1) A cementitious binder and aggregate are thoroughly mixed.

(2) The cement-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 feedwheel, rotor, or feed bowl. Some equipment uses air pressure alone (orifice feed) to deliver the material into the hoses.

(4) The material is carried by compressed air through the delivery hose to a nozzle body. The nozzle body is fitted inside with a water ring, through which water is introduced under pressure and intimately mixed with the other ingredients.

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

1.6.2 *Wet-mix process*-This process consists of the following steps:

(1) All of the ingredients, including mixing water, but usually excluding accelerator, 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 displacement or conveyed by compressed air to a nozzle.

(4) Accelerator is usually added at the nozzle.

(5) Additional air is injected at the nozzle to increase velocity and improve the gunning pattern.

(6) The mortar or concrete is jetted from the nozzle at high velocity onto the surface to be shotcreted.

1.6.3 *Comparison of the processes*-Shotcrete suitable for normal construction requirements can be produced by either process. However, differences in capital and maintenance cost of equipment, operational features, suitability of available aggregate, and placement characteristics may make one or the other more attractive for a particular application. Differences in operational features and other properties which may merit consideration are given in Table 1.1.

Coarse aggregate shotcrete uses a lower cement factor, with a corresponding reduced admixture requirement, and for some applications offers certain economic advantages. However, for both dry- and wet-mix processes, coarse aggregate shotcrete has higher rebound, is more difficult to finish, and cannot be used for thin layers.

TABLE 1.1-COMPARISON OF DRY- AND WET-MIX PROCESSES

Dry-mix process	Wet-mix process
1. Instantaneous control over mixing water and consistency of mix at the nozzle to meet variable field conditions.	1. Mixing water is controlled at the delivery equipment and can be accurately measured
2. Better suited for placing mixes containing lightweight aggregates, refractory materials and shotcrete requiring early strength properties	2. Better assurance that the mixing water is thoroughly mixed with other ingredients
3. Capable of being transported longer distances	3. Less dusting and cement loss accompanies the gunning operation
4. Start and stop placement characteristics are better with minimal waste and greater placement flexibility	4. Normally has lower rebound resulting in less material waste
5. Capable of higher strengths	5. Capable of greater production

1.7-Properties

Although information on shotcrete construction and application is available in the literature, there is presently a scarcity of useful engineering data and the information available shows a wide range of values. This is attributable, in part, to a lack of standard testing procedures, variations in constituent material quality and gradation, nonuniformity of application techniques, the absence of testing standards, and difficulty in correlating factors between test specimens and in-place shotcrete cores.

In general, properly applied shotcrete is a structurally sound and durable construction material and exhibits excellent bonding characteristics with concrete, masonry, rock, steel, and many other materials. Table 1.2 contains recent test data which illustrates the bonding qualities of shotcrete. It has high strength, low absorption, good resistance to weathering and many kinds of chemical attack, and has excellent fireproofing qualities. These favorable properties are contingent on good specifications and materials, and proper surface preparation, mixing, shotcrete application, and supervision.

The physical properties of sound shotcrete are comparable or superior to those of conventional mortar or concrete having the same composition.

The water-cement ratio for dry-mix shotcrete in-place normally falls within a range of 0.30 to 0.50 by weight and 0.40 to 0.55 for wet-mix shotcrete. Most published values for 28-day strength are in the range of 3000 to 7000 psi (20 to 48 MPa), although dry-mix shotcrete in some tests has developed strengths in excess of 10,000 psi (69 MPa). It is recommended that strengths higher than 5000 psi (34.5 MPa) be specified only for carefully engineered and executed shotcrete work.

The drying shrinkage of shotcrete varies with the mix

TABLE 1.2-BOND STRENGTH OF SHOTCRETE

Sample No.	Compressive strength of shotcrete cores, psi (MPa)	Bond strength in shear, psi (MPa)
A. Dry-mix shotcrete on old concrete		
1	5850 (40.3)	720 (5.0)
2	7140 (49.2)	598 (4.1)
3	5900 (40.7)	422 (2.9)
4	5410 (37.3)	520 (3.6)
5	7060 (48.7)	874 (6.0)
6	4620 (31.9)	411 (2.8)
7	4580 (31.6)	508 (3.5)
B. Dry-mix shotcrete on old wet-mix shotcrete		
8	4780 (33.0)	560 (3.9)
9	4360 (30.1)	530 (3.7)
10	4660 (32.1)	500 (3.4)
C. Wet-mix shotcrete on old wet-mix shotcrete		
11	4810 (33.2)	131 (0.9)
12		181 (1.3)
13	4420 (30.5)	243 (1.7)
14		220 (1.5)
15	4860 (33.5)	336 (2.3)

Data is from a single project. It is presented for illustrative purposes only.
All tests on 6 in. (150 mm) diameter cores.
Shotcrete placed by dry method. Base shotcrete in Section B was by wet mix.
Concrete surface in Sections A and C prepared by sandblasting; in Section B no preparation.
Shear test conducted by "guillotine" method where load is applied parallel to the bonded surface.

proportions used, but generally falls within the range of 0.06 and 0.10 percent. This is slightly higher than most low slump conventional concrete which can be placed in heavier sections using larger aggregate and leaner mixes. Most shotcrete has a high cement factor and, therefore, has a greater potential for drying shrinkage cracking which may require a closer control joint spacing or increased use of reinforcing mesh or steel.

The coefficient of thermal expansion of shotcrete approximates that of reinforcing steel, thereby minimizing internal stress development. The unit weight of good shotcrete is usually between 140 and 150 pcf (2230 to 2390 kg/m^3), about the same as conventional concrete. The modulus of elasticity generally falls between 2.5 $\times 10^6$ and 6.0 $\times 10^6$ psi (17 $\times 10^3$ to 41 $\times 10^3$ MPa)[3], again similar to conventional concrete. The freeze-thaw durability of shotcrete in laboratory tests and under field exposure has generally been good. However, problems can develop with even the best shotcrete when it is applied to a nondurable or improperly prepared substrate.

It should be stressed that the properties and performance of shotcrete are largely dependent on the conditions under which it is placed. They may also be dependent on the characteristics of the particular equipment selected, and ultimately on the competence and experience of the application crew.

1.8-Shotcrete applications

Shotcrete can be used in lieu of conventional concrete in most 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 Fig. 1.2). Reinforcing details may complicate the use of shotcrete but it 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 and/or variable thickness are required, or normal casting techniques cannot be employed. The excellent bond of shotcrete (Table 1.2) to a number of materials is sometimes an important design consideration.

Shotcrete applications can be classified under three general headings: (1) Conventional-using portland cement,

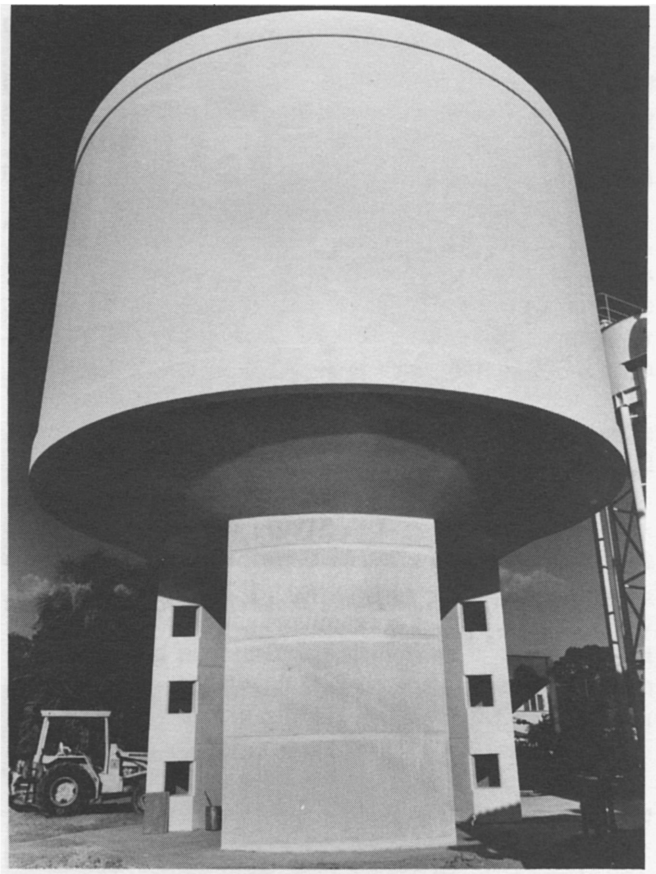


Fig. 1.1-Elevated prestressed shotcrete water storage tank

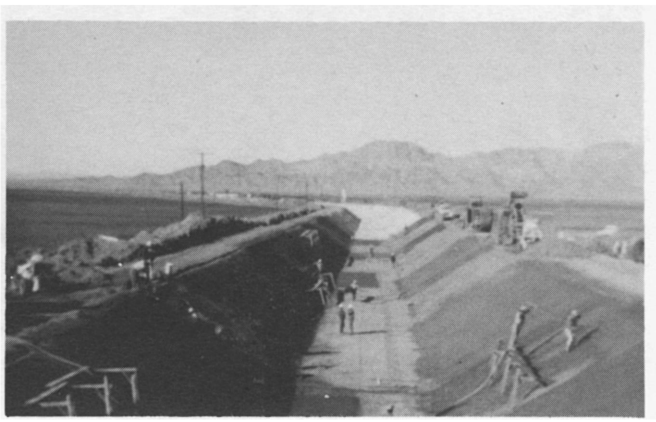


Fig. 1.2-Dry-mix shotcrete lining being installed in a large water irrigation channel in Arizona

conventional aggregates, and ordinary admixtures where appropriate; (2) Refractory-Using high temperature binders and refractory aggregates; and (3) Special-Using proprietary combinations of binder and aggregate, or conventional shotcrete with special admixtures.

1.8.1 *Conventional shotcrete*-Conventional shotcrete has been and continues to be the largest application for shotcrete and includes the following:

1.8.1.1 *New structures.* Roofs, thin shells, walls, prestressed tanks, buildings, reservoirs, canals, swimming pools, boats, sewers, foundation shoring, ductwork and shafts, and artificial rock (Fig. 1.3a, 1.3b).

Fig. 1 .3a-Applying wet-mix shotcrete as scour protection to a spawning channel

Fig. 1.3b-Applying wet-mix shotcrete in a swimming pool

1.8.1.2 *Linings and coatings.* Over brick, masonry, earth, and rock; underground support, tunnels, slope protection and erosion control, fireproofing steel, steel pipeline, stacks, hoppers and bunkers, steel, wood, and concrete; and pipe protection, and structural steel encasement (Fig. 1.4).

1.8.1.3 *Repair.* Deteriorated concrete in bridges, culverts, sewers, dams, reservoir linings, grain elevators, tunnels, shafts, waterfront structures, buildings, tanks, piers, seawalls, deteriorated brick, masonry, and steel structures (Fig. 1.5).

1.8.1.4 *Strengthening and reinforcing.* Concrete beams, columns and slabs, concrete and masonry walls, steel stacks, tanks, and pipe.

1.8.2 *Refractory shotcrete*-Refractory shotcrete construction had its start in the middle 1920s and was used primarily for repair and maintenance of furnace linings. Because of the speed of installation and general effectiveness of the process it has found great favor in the refractory industry. Today it 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, nonferrous metal, chemical, mineral and ceramic processing plants, steam power generation, and incinerators.

1.8.3 *Special shotcretes*-Special shotcretes include proprietary mixtures for corrosion and chemical resistant applications. Portland cement and aggregate with admixtures are used to produce special properties. Included among the former are the sodium and potassium silicates, magnesium phosphates, and polymers. Among the latter, are portland cement shotcretes using accelerating, retarding, and pozzolanic admixtures. It also includes a new group of materials classified as polymer modified shotcretes. These special

Fig. 1.4-Applying steel fiber reinforced dry-mix shotcrete against a rock embankment to stabilize the slope. Note that welded wire fabric is not required

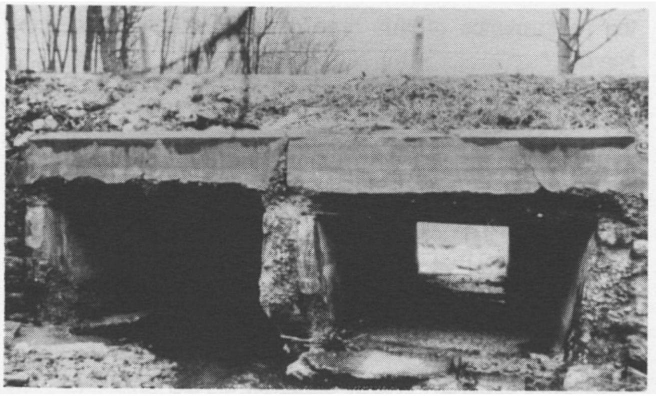


Fig. I.5a-Deteriorated double box culvert showing advanced deterioration and distress prior to repair

Fig. I.5b-Concrete in culvert partially restored with shotcrete with a "natural"' or gun finish. Final lines are uneven to match the environment, and also reduce finishing costs

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.

1.9-New developments, future uses, and potential

1.9.1 *General*-The future of shotcrete is limited only by the speed of development of new materials, equipment, and techniques. A prime example of recent expansion in the use of shotcrete is in early ground support for tunnel construction which became a major shotcrete application in the early 1970s. Improvements in accelerating admixtures, the use of steel fibers, and specially designed equipment including robot and remote shotcrete devices have spurred the development of ground support techniques competitive with conventional steel rib supports.

1.9.2 *Refractory shotcrete*-Refractory shotcrete is another application which is making great progress and now provides a viable alternative to traditional methods of refractory construction. As material quality and versatility improves, providing enhanced physical properties, shotcrete techniques could replace the more conventional installation procedures. Hot gunning procedures for high temperature installation and "bench" gunning (see Fig. 8.5) for thick layers have opened new fields for refractory shotcrete use.

1.9.3 *Fibrous shotcrete*-The use of short fibers of steel or other materials in conventional and refractory shotcrete has been gaining favor during the past few years. The fibers can provide improved flexural and shear strength, toughness, and impact resistance. For refractory shotcrete, fibers increase resistance to thermal shock, temperature cycling damage, and crack development. Some specific future uses where fibrous 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.

Although most uses of steel fiber reinforcement has been in dry-mix shotcrete, the material is also applicable to wet-mix shotcrete application. Special care, and sometimes special equipment, may be required in adding fibers to the shotcrete mix to prevent clumping or kinking of the fibers, and to assure that they are properly proportioned. The use of fibers in shotcrete is a relatively new development, and much has still to be learned about the optimum size and shape of the fibers, methods of addition to both wet- and dry-mix shotcretes, and other factors. (Refer to ACI 506.lR.)

1.9.4 *Polymer portland cement shotcrete*-Polymer portland cement shotcrete is another innovation that shows promise. The addition of certain latex formulations to a conventional portland cement shotcrete mix improves flexural and tensile strengths, and may improve bond as well as reduce absorption and penetration of chlorides. A potential major application of this material is the repair of concrete bridge and marine substructures, and structures in industrial plants that are under chemical attack.

1.9.5 *Gun casting*-Gun casting is a placement technique which is an outgrowth of the standard dry-mix shotcrete process. In place of the standard nozzle, a casting head is used in conjunction with standard dry-mix equipment. This slows the velocity of the material on exit, almost eliminating rebound and minimizing the finishing required. It has found extensive use in certain sectors of the refractory industry, but also is used in normal shotcrete installation. It increases the utility of the dry-mix gun, permits placement of concrete in close restricted quarters and at distant or inaccessible locations. Form requirements are minimal while labor and material costs are usually reduced (Fig. 1.6).

1.9.6 *Research and development*-The use of shotcrete to speed and mass produce ferrocement shapes, silos, storage tanks, conduits, and other structures has possible potential. Composites of shotcrete and polystyrene or polyurethane foam, special fiberglass and other plastics forming a sandwich construction is another possibility. The ability of the shotcrete process to handle and place materials which have almost instantaneous hardening capabilities should also provide many future applications. Some areas of future research and development are:

(a) Rational shotcrete design
(b) Nozzle design
(c) In-place testing techniques
(d) Materials
(e) Equipment mechanization
(f) Substrate evaluation

(g) Process automation

As more aspects of the shotcrete method from design to installation are developed, its potential for use in the construction industry will increase.

Fig. 1.6-Gun casting refractory castable

CHAPTER 2-MATERIALS

2.1-Introduction

Since shotcreting is a method of placing mortar or concrete, materials which result in high quality mortar or concrete are suitable for producing high quality shotcrete.

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 Section 2.5 of ACI 301.

2.3-Cement

2.3.1 *Portland cement*-Cement conforming to ASTM C 150, or C 595 may be used in shotcreting.

2.3.2 *Calcium aluminate cement*-Calcium aluminate or high alumina cement is a rapid hydration cement that is used mainly for refractory applications. It also may provide resistance to certain acids. The use of calcium aluminate cement should be fully investigated for any particular application because of its fast setting properties, its high early heat of hydration, the possible reduction of long-term strength by the process known as conversion, and potential differences between brands. Additional information on the performance of this type of cement is published by Neville.*

2.4-Aggregate

2.4.1 *Normal weight aggregate*-Normal weight aggregate for shotcrete should comply with the requirements of ASTM C 33. The combined aggregate should meet one of the gradations shown in Table 2.1. Gradation No. 1 should be used for fine aggregate shotcrete. Sand for finish or flash coats may be finer than Gradation No. 1, however, the use of finer sands generally results in higher drying shrinkage. The use of coarser sands generally results in more rebound. When coarse aggregates as in Gradation No. 3 are used, the coarse and fine aggregates should be weighed separately to avoid poor gradation because of segregation. Oversize pieces of aggregate should be rejected by screening, as they are likely to cause plugging of the hose or nozzle.

Aggregates failing to comply with the gradations shown in Table 2.1 may be used if preconstruction testing proves that they give satisfactory results or if acceptable service records are available.

2.4.2 *Lightweight aggregates*-Lightweight aggregates if used in shotcrete should conform to ASTM C 330.

TABLE 2.1 -GRADATION LIMITS FOR COMBINED AGGREGATES

Sieve size, U.S. standard square mesh	Percent by weight passing individual sieves		
	Gradation No. 1	Gradation No. 2	Gradation No. 3
¾ in. (19mm)	–	–	100
½ in. (12 mm)	–	100	80-95
⅜ in. (10 mm)	100	90-100	70-90
No. 4 (4.75 mm)	95-100	70-85	50-70
No. 8 (2.4 mm)	80-100	50-70	35-55
No. 16 (1.2 mm)	50-85	35-55	20-40
No. 30 (600 µm)	25-60	20-35	10-30
No. 50 (300 µm)	10-30	8-20	5-17
No. 100(150 µm	2-10	2-10	2-10

2.5-Water

2.5.1 *Mixing water*-Mixing water should be clean and free from substances which may be injurious to concrete or steel. It is recommended that potable water be used. If potable water is not available, the water must be tested to assure that strengths of mortar cubes made with it are at least 90 percent of that of mortar cubes made with distilled water (see also Section 3.4 of ACI 318).

The soluble chloride ion content in prestressed shotcrete, shotcrete containing dissimilar metals, or reinforced shotcrete exposed to seawater should not exceed the values in Table 4.5.4 of ACI 318. Total chloride ions should include that in the cement, water, aggregates, and admixtures.

2.5.2 *Curing water*-Curing water should be free from substances that may be injurious to concrete. Water for curing of architectural shotcrete should be free from elements that will cause staining.

*Neville, Adam, "High Alumina Cement-Its Properties. Applications, and Limitations," *Progress in Concrete Technology, CANMET,* Energy, Mines and Resources, Ottawa, 1980, pp. 293-331.

2.6-Bonding compounds

Bonding compounds are generally not recommended for use in shotcrete work, as the bond of shotcrete to *properly prepared* substrates is normally excellent. If required, epoxy or latex materials are available. If used, the manufacturer's instructions should be followed. Bonding compounds improperly used can act as bond breakers. It is recommended that any extensive use of a bonding compound should be preceded by preconstruction trials.

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. It is recommended that the use of admixtures in shotcrete be tested prior to large scale use to determine that the advantages expected are obtained. Admixtures should meet the requirements of the appropriate ASTM specification if such a specification is available.

Admixtures for shotcrete generally fall into the following categories.

2.7.1 *Accelerators*

2.7.1.1 Calcium chloride, meeting the requirements of ASTM D 98 may be used as an accelerator, under certain conditions, where early set or rapid strength development is required. Calcium chloride should not be used in amounts greater than 2 percent by weight of the cement in the shotcrete and chloride ion contents should not exceed the limits in Section 2.5.1.

2.7.1.2 A number of other accelerators are available for use with shotcrete. These materials are capable of inducing initial set within a few minutes of their introduction into the shotcrete mix. This property is useful in tunnelling or wet applications 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 more quickly build up layers of shotcrete applied to vertical or overhead surfaces. The use of some rapid set accelerators results in considerable reductions of ultimate shotcrete strength, and they should be thoroughly evaluated before use. Some of these admixtures are caustic and care should be exercised in handling them. An ASTM specification for compatibility of shotcrete accelerators and portland cement is under preparation.

2.7.2 *Air-entraining admixtures*-Air-entraining admixtures do not entrain air in dry-mix shotcrete. Wet-mix shotcrete that will be exposed to freeze-thaw cycles should be air-entrained. Air entrainment tends to make some mixes more workable and may reduce rebound. Data is available to show that a significant quantity of the entrained air in wet mixtures is lost in gunning, but this may be offset by increasing the quantity of air entraining agent. Air-entraining admixtures should meet the requirements of ASTM C 260.

2.7.3 *Latex*-A description of latex modified shotcrete is presented in Sections 1.8.3 and 1.9.4.

2.7.4 *Pozzolans*-Pozzolanic admixtures may be used in shotcreting. Pozzolans may enhance workability or pumpability of some wet-mix shotcretes. They may provide more resistance to sulfate attack and to alkali-aggregate reaction if reactive aggregates must be used. The use of pozzolanic admixtures on an equal weight replacement for cement may result in slower early strength gain. Pozzolanic admixtures should meet the requirements of ASTM C 618.

2.7.5 *Water-reducing and retarding admixtures*-Water-reducing admixtures for wet-mix shotcrete should conform to ASTM C 494. Such admixtures are normally not used in dry-mix shotcrete.

Retarding admixtures are not normally used in shotcrete work. If used, they should conform to ASTM C 494, Type D.

2.8-Reinforcement

2.8.1 *Steel fibers*-Fibrous reinforcement has been used in shotcrete to reduce crack propagation, to increase flexural strength and to improve ductility, toughness and impact resistance. Steel fibers between ½ and 1½ in. (12 and 40 mm) long, in amounts up to about 2 percent by volume of the shotcrete, have been used.

2.8.2 *Reinforcing bars*-Reinforcing bars used in shotcrete should conform to ASTM A615, A616, A617, A 706, A 767, or A 775.

Shotcrete construction requires care in the spacing and arrangement of reinforcing, as heavy concentrations of steel interfere with proper shotcrete placement. The use of bars larger than #5 (No. 15M) requires exceptional care to properly encase them with shotcrete. Reinforcements should be free from oil, loose rust, mill scale, or other surface deposits that may affect bond to shotcrete.

2.8.3 *Wire fabric*-Welded wire fabric should conform to ASTM A 185, or ASTM A 497 and may be uncoated or galvanized.

The welded intersections should be spaced no further apart than 12 in. (300 mm) for plain wire or 16 in. (400 mm) for deformed wire. A commonly used fabric is one having No. 8 or 10 gage (4.1 mm or 3.4 mm) wire, spaced 4 in. (100 mm) in both directions. In no case should the wires be spaced less than 2 in. (50 mm) apart (Section 5.4.2).

Note: The use of galvanized mesh is often specified to reduce the possibility of corrosion of the mesh in aggressive environments. There is now also available epoxy coated mesh which may also find use in environments with potential reinforcing steel corrosion. Galvanizing shall conform with ASTM A 385 and A 641.

2.8.4 *Prestressing steel*-Prestressing steel should be in conformance with ASTM A 416, A 421 or A 722.

2.8.5 *Other forms of steel*-other steel bars and shapes used should conform to requirements of ACI 318, Chapter 3, Materials.

CHAPTER 3-EQUIPMENT

3.1-Introduction

The successful application of shotcrete requires properly operated and maintained equipment. The equipment for a project should be chosen by the contractor only after a careful evaluation of the specifications, size, and character of the work; job site conditions; the availability and quality of local materials; labor; and time available. A basic complement of equipment for shotcreting usually consists of, but is not limited to, a gun or pump, compressor, mixer, nozzles, and miscellaneous hoses.

3.2-Dry-mix guns

Dry-mix shotcrete equipment may be divided into two distinct types (a) single or double chamber guns and (b) continuous feed guns, usually called rotary guns.

3.2.1 *Single and double chamber guns*

3.2.1.1 Single chamber or batch guns provide intermittent operation by placing a charge of material into the chamber and closing and pressurizing the chamber, causing the material to feed into a delivery pipe or hose. When the chamber is empty, it is depressurized and refilled, and the operation repeated (Fig. 3.1). Some single chamber guns utilize a rotating feed wheel to give a positive metering action to the material flow (Fig. 3.2).

3.2.1.2 Double chamber guns allow for continuous operation by using the upper chamber as an airlock during the charging cycle. Fig. 3.3a and 3.3b show the configuration of this type equipment and Fig. 3.4 shows the operating sequence. Most double chamber guns utilize the rotating feed wheel principle.

3.2.2 *Continuous feed guns*-This type of 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 may be used for wet-mix applications.

3.2.2.1 The barrel type, as shown in Fig. 3.5a and 3.5b, utilizes sealing plates on the top and bottom of the rotating element. 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.

3.2.2.2 The feed bowl type, as shown in Fig. 3.6a and 3.6b utilizes 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 discharged into the outlet neck when that particular cavity is indexed under the sealing segment, air being injected down one leg of the U and carrying the material into the material hose.

3.2.3 *Precautions*-Care must be exercised not to clean 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 mix 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. The hopper screen of the rotary gun should be in place whenever the unit is operating to avoid accidents connected with the rotating agitator. Goggles, dust masks, or respirators should be used by the gun operator at all times 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 fossil fuel as power for the delivery equipment.

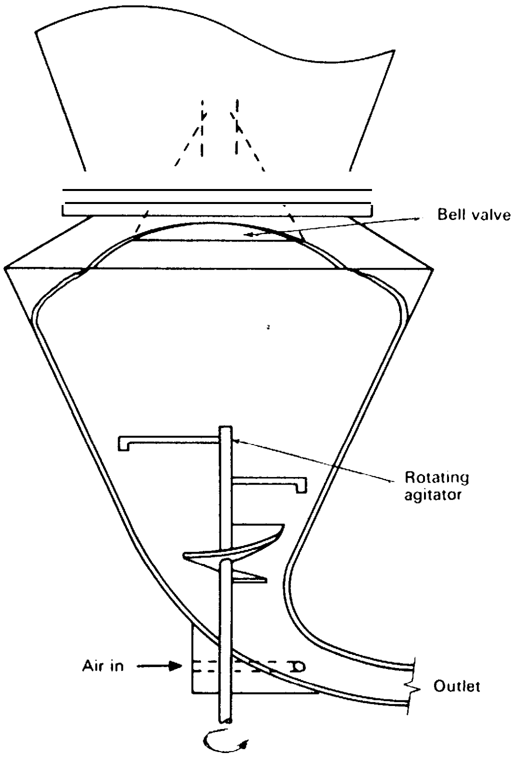


Fig. 3.1-Schematic of single chamber gun (dry process). (From Reference 8)

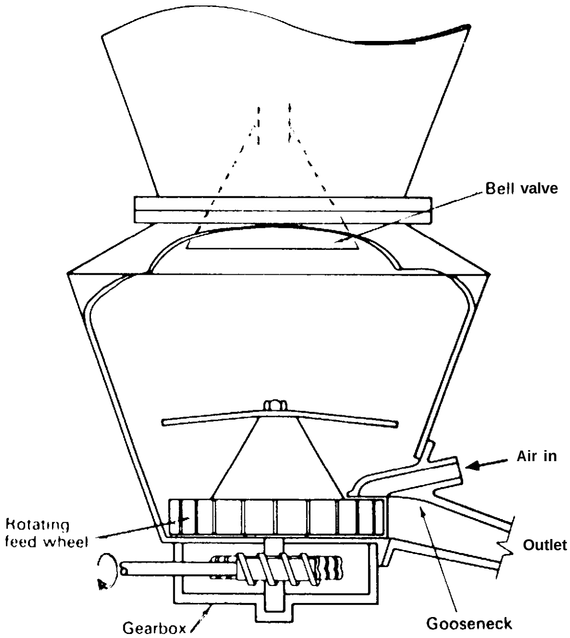


Fig. 3.2-Schematic of single chamber gun with feed wheel (dry process). (From Reference 8)

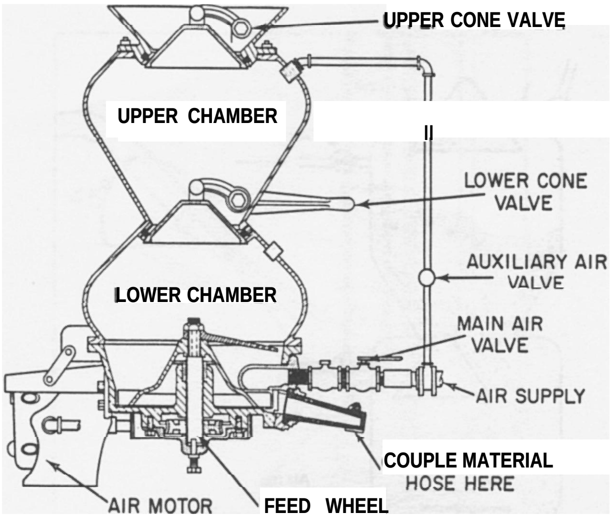


Fig. 3.3a-Schematic of double chamber gun (dry process)

Fig. 3.3b-Double chamber gun (dry process)

3.3-Wet mix guns

Two types of equipment are generally used for the wet-mix process (a) pneumatic feed and (b) positive displacement.

3.3.1 *Pneumatic feed guns*

3.3.1.1 The pneumatic feed gun introduces slugs of material into the delivery hose with compressed air being added at the discharge sump and at the nozzle to increase the velocity of the mixture (Fig. 3.7).

This machine has a dual chamber tank and two-way valve which allows for mixing materials and a continuous flow operation.

3.3.1.2 The rotary type dry process machines have been modified to handle wet or plastic mixes fed into their rotor cavities. Compressed air is usually not introduced at the nozzle with this type machine.

3.3.2 *Positive displacement* guns-Positive displacement wet-process equipment uses mechanical, air, or hydraulic pressure to force a solid column of shotcrete through the hose in a continuous stream to the nozzle. Air is injected at the nozzle to break up the stream and increase exit velocity.

3.3.2.1 Modified single chamber dry process machines similar to that illustrated in Fig. 3.1 can be used with a wet mix except that air is not introduced in the outlet and the chamber is not emptied. Since the application is intermittent and friction losses are high, this type of equipment has limited use.

3.3.2.2 A peristaltic type or squeeze pump uses mechanical rollers to squeeze the concrete through a tube into a delivery hose (Fig. 3.8). Compressed air is injected at the nozzle to increase the exit velocity of the mixture.

3.3.2.3 Wet-mix shotcrete can be applied using positive displacement pumps equipped with mechanical or hydraulic powered pistons with a variety of cycling valves and surge-reducing devices. A typical piston type unit is illustrated in Fig. 3.9. Compressed air is used at the nozzle to increase the exit velocity of the mix.

3.3.3 *Precautions-The* manufacturer's recommendations for the safe operation and cleaning of wet-process guns should be followed explicitly. The precautions listed in Section 3.2.3 concerning the use of personal protection, outlet connections, and working conditions apply in the wet process also.

3.4-Air requirements

A properly operating air compressor of ample 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 mode of operation. It is advisable to check the gun manufacturer's recommendations for required compressor capacity.

3.4.1 *Dry process*

3.4.1.1 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 must 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 nozzle above the

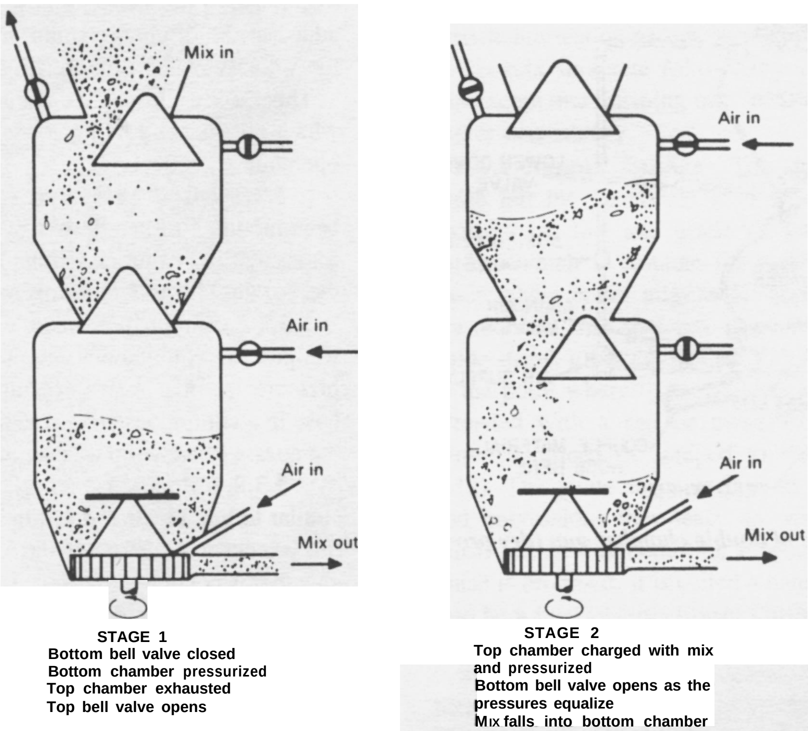


Fig. 3.4-Operating sequence of double chamber gun. (From Reference 8)

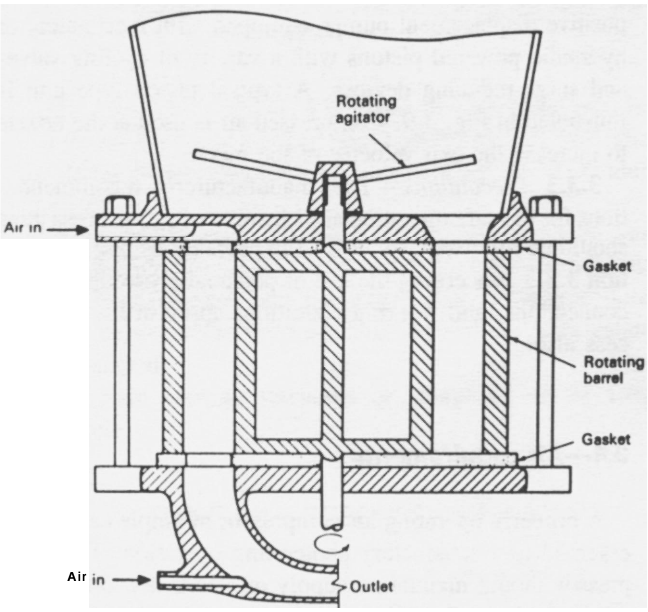


Fig. 3.5a-Schematic of rotary barrel gun (dry process). (From Reference 8)

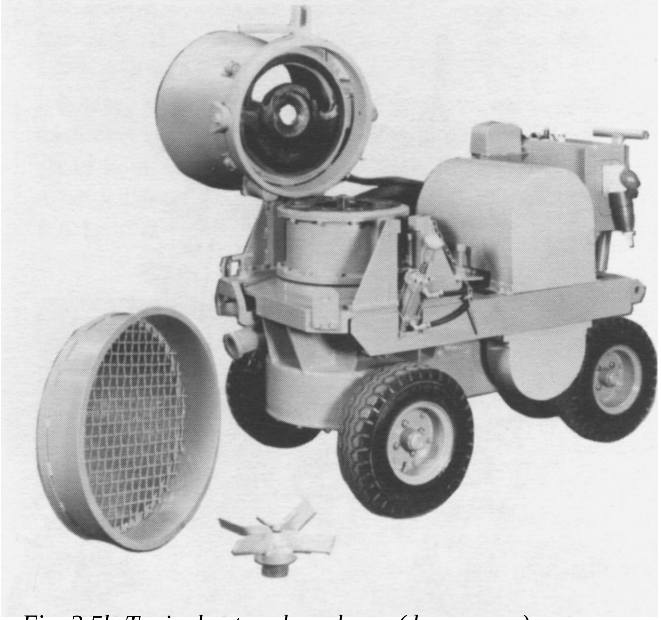


Fig. 3.5b-Typical rotary barrel gun (dry process)

gun, and other air demands, will all affect the air requirements of a particular equipment layout.

3.4.1.2 The operating air pressure is the pressure driving 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 specific weight of the material mix, the height of the nozzle above the gun, the number of hose bends, plus other factors. A rule of thumb is that operating pressures should not be less than 40 psi (275 kPa) when 100 ft (30 m) or less of material hose is used and the pressure should be increased 5 psi (35 kPa) 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 process*

3.4.2.1 Pneumatic feed wet process guns require less air for a given hose size than dry equipment, but operate at higher back pressures.

3.4.2.2 Positive displacement wet process equipment requires a supply of at least 105 cfm ($3 m^3/min$) at 100 psi (700 kPa) at the air ring for proper operation.

3.4.3 *Air supply lines*-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

TABLE 3.1 -COMPRESSOR CAPACITIES AND HOSE DIAMETERS

Material hose inside diameter		Compressor capacity	
in.	mm	cfm at 100 psi	m3/min at 700 kPa
1	25	350	10.0
1¼	32	450	12.5
1½	38	600	17.0
2	51	750	21 .0
2½	64	1000	28.0

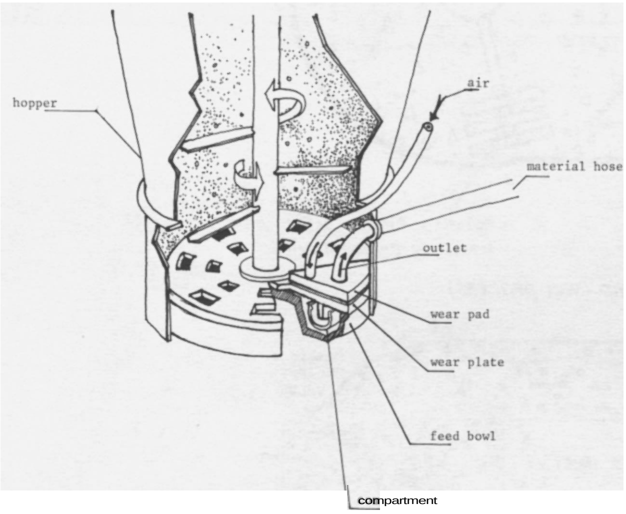


Fig. 3.6a-Schematic of rotary feed bowl type gun (dry process)

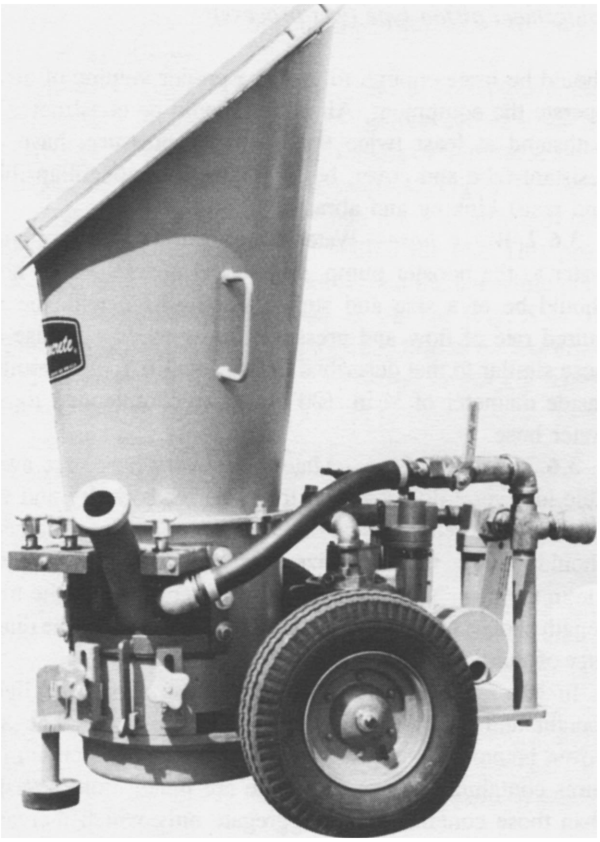


Fig. 3.6b-Typical feed bowl gun (dry process)

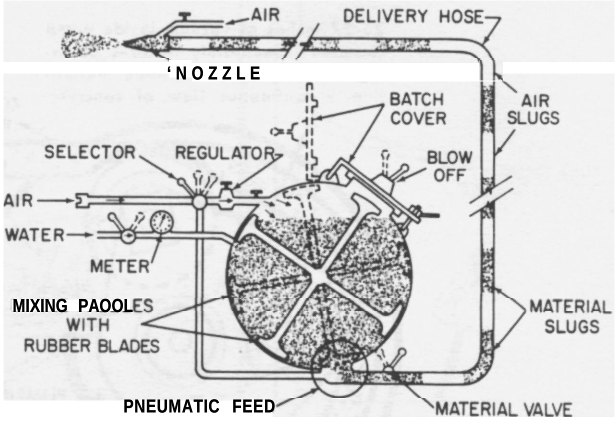


Fig. 3.7-Schematic of pure pneumatic feed gun (wet process)

except for the positive displacement wet process equipment where the air hose to the nozzle is ¾ in. (20 mm) or greater.

3.5-Mixing equipment

Most shotcrete applications utilize mixtures that are prepared in the field using portable mixing equipment or delivered to the job site in mixer trucks from a conveniently located ready-mixed concrete plant (Fig. 3.10). Mixing equipment for dry-mix shotcrete work falls into two general categories (a) batch and (b) continuous. Both are available in a range of types, sizes, and manufacture. The batch type, as shown in Fig. 3.1la and 3.11 b, uses a drum mixer with fixed integral blades or rotating paddle with or without an elevating conveyor. The continuous type, shown in Fig. 3.12, uses a trough with screw or auger which mixes and elevates at the same time. A hopper is sometimes used in high production units of both these types to collect and feed the mixture as required. Water metering systems are also available to predampen the mixture.

3.5.1 *Batch mixing*-The equipment for proportioning mixtures varies from the simple calibrated box to highly sophisticated electronic devices. 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 thorougly mixing and supplying a homogeneous and consistent mix. The mixer should be self-cleaning, capable of discharging all mixed material so as to prevent buildup or accumulations of hydrated and caked materials in the mixing bowl and conveyor. It should be thoroughly cleaned as necessary and at least once daily at the conclusion of work.

3.5.2 *Continuous mixing*-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 means of variable speed augers or belt feed systems, or a combination of both. This equipment should conform with ASTM C 685.

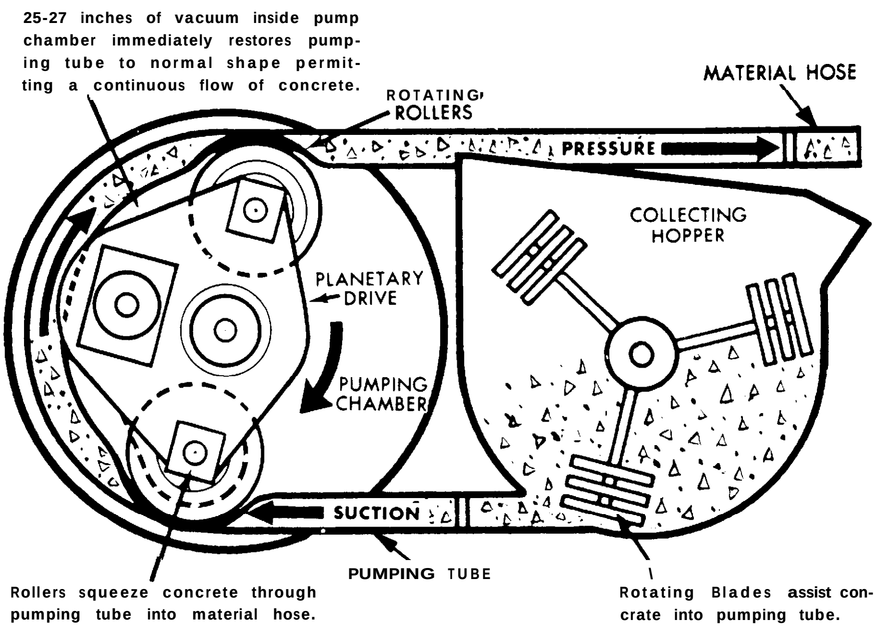


Fig. 3.8-Schematic diagram of squeeze pump (wet process)

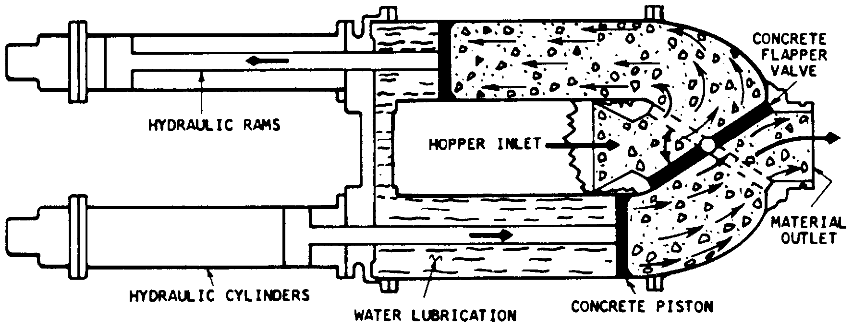


Fig. 3.9-Schematic diagram of positive displacement piston type (wet process)

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

3.5.3 *Precautions*-The major potential hazard in the use of mixers is the exposure of personnel to moving parts. It is essential that the operator be taught to properly load the mixer and the safety precautions to follow in start-up and operation of the mixer. All chains, belts, elevating screws, and conveyor belts, and other moving parts, should be covered appropriately while the unit is in operation. Shovels, bars, rakes, or other objects should not be inserted near or in moving parts of the mixer. It is equally important to use care during the cleaning of mixing equipment.

3.6-Hose

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 must be analyzed and evaluated when selecting the appropriate hose. Hose couplings should not obstruct flow, have proper safety restraints for blowout protection, and be quick acting.

3.6.1 *Air hose*-Air hose is used to supply air to the shotcrete gun, the nozzle in the wet process, the blow pipe, and other air operated equipment and tools. The air hose should be large enough to insure a proper volume of air to operate the equipment. Air hoses should be constructed to withstand at least twice the operating pressure, have oil resistant tube and cover, be light, flexible, noncollapsible, and resist kinking and abrasion.

3.6.2 *Water hose*-Water hose is used for supplying water to the booster pump, mixer, and nozzle. Water hose should be of a size and strength compatible with the required rate of flow and pressure. Some applicators use air hose similar to that described in Section 3.6.1. A minimum inside diameter of ¾ in. (20 mm) is recommended for all water hose.

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 mix. When gunning steel fiber mixtures the fiber length should preferably be no more than one-half the diameter of the hose.

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. Where static electricity is a problem, usually because a dryer and optimum mix is being gunned, a special hose incorporating a ground wire should be used.

Positive displacement wet shotcrete is pumped at higher pressures than other methods and requires hose and couplings that will resist higher operating pressures.

3.6.4 *Precautions*-All hose (water, air, and materials) are subject to rupture and coupling breaks. To minimize these risks it is important to use hose with a high factor of safety capable of taking pressures of twice the working load pressure. In addition, safety chains or cables should be installed on all couplings to minimize hose whip should the coupling break loose. Material hose plugging can cause coupling breaks, and/or hose rupture during operation with the possibility of hose whip and skin burn. Hoses become plugged when oversized particles or objects find their way into the mix, the hose diameter is reduced in section by material caking, or the volume of air is insufficient to move the material in the hose.

Fig. 3.10-Ready-mixed concrete truck delivering material to wet-mix shotcrete pump

Plugging can be reduced by maintenance, by screening the material, maintaining proper moisture content, and properly proportioning the mixture for the equipment and materials available. Cleaning or unplugging the hose using air pressure can create a hazard to the nozzleman. High pressures are used to unblock the line and this can cause severe whipping and vibration of the hose and nozzle as the plug exits.

Rupturing of material hose is caused by uneven wear of the hose wall especially on the outer side of the curved or looped hose. Hose 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 since a break in a heavy metal coupling can pose a potential hazard.

In the dry-mix process, material with low moisture content can create static electricity buildup while passing through the hose which can shock the nozzleman and cause him to lose control of the nozzle. This problem can be avoided by grounding the gun, using a special antistatic hose and maintaining the proper predampening moisture in the aggregate.

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, to premix water and solids, and to provide uniform distribution of the mixture. Ideally, the 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.

The dry-mix nozzle consists of a nozzle tip, water ring, control valve, and water body as shown in Fig. 3.13. The tip can be made of rubber, elastomer material, or of metal with a rubber liner. They are of variable length and may be straight, tapered, rifled, single or double venturi, and 90 deg. See Fig. 3.14 for examples.

A typical wet-mix nozzle consists of a rubber nozzle tip, an air injection ring, control valve, and housing. Fig. 3.15 shows an example.

Fig. 3.16 illustrates a hydromix nozzle which separates the nozzle from the nozzle body with a 12 to 36 in. (300 to 900 mm) section of delivery hose. This configuration allows

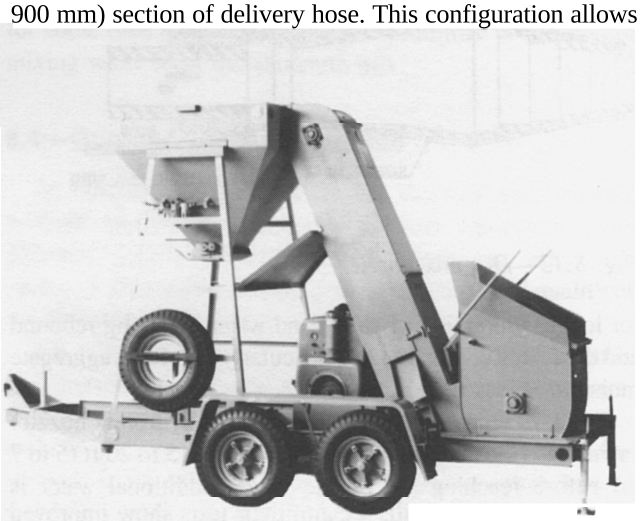


Fig. 3.11a-Batch mixer with elevator for double chamber gun

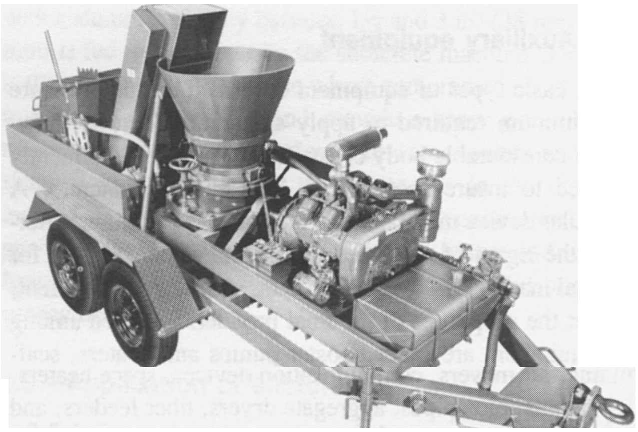


Fig. 3.11b-Batch mixer with elevator for rotary gun

Fig. 3.12-Continuous proportioning mixer with screw elevator has three bins for fine and coarse aggregate and cement

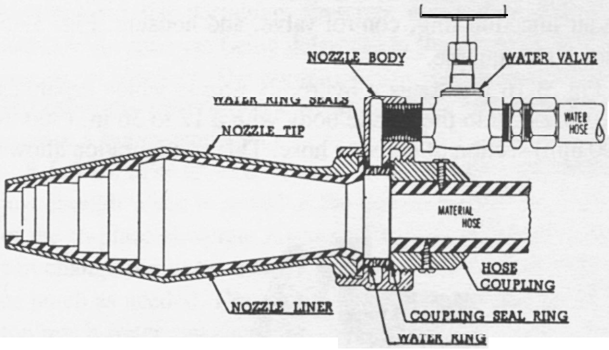


Fig. 3.13-Dry-mix nozzle

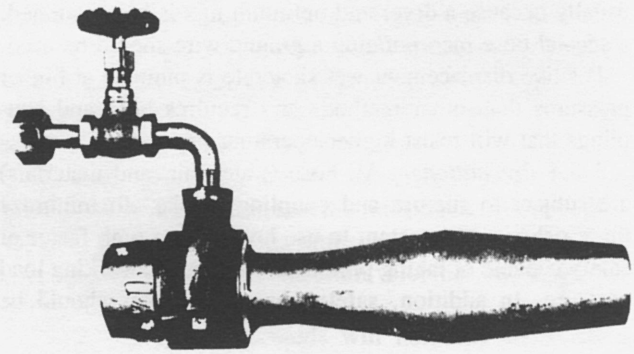
for longer premixing of solids and water, reducing rebound and dust. It is claimed to be particularly helpful if aggregate moisture is less than optimum.

Fig. 3.17 represents an extension of the hydromix nozzle. In this case the material is prewetted about 15 to 20 ft (5 to 7 m) before reaching the nozzle where additional water is injected. Ward and Hills[12] claim their tests show improved physical properties for the shotcrete when installed using the "long" nozzle. Others have indicated that they experienced increased yield due to a much lower rebound loss factor.

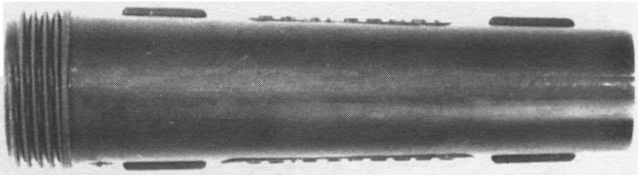
3.8-Auxiliary equipment

The basic types of equipment described to this point are the minimum required to apply shotcrete. There is, however, a considerable body of auxiliary equipment frequently required to insure 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, blowpipes, aggregate dryers, fiber feeders, and admixture dispensers.

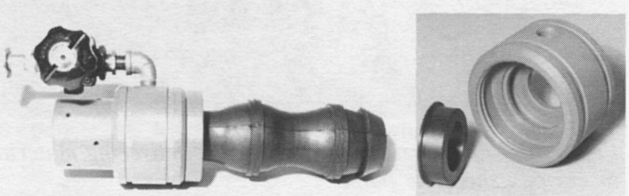
3.8.1 *Water booster pumps*-In dry-mix applications, a pressure boosting device is needed when available pressure is inadequate to properly wet the mix. A minimum of 60 psi



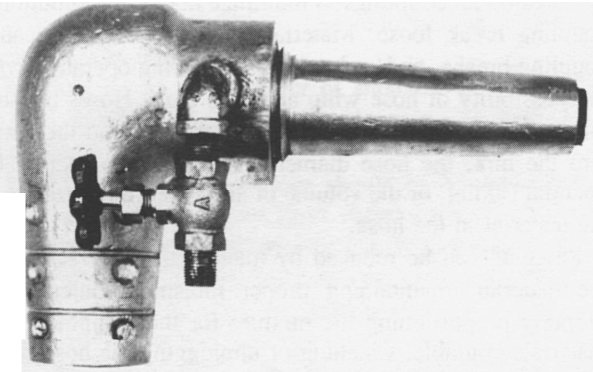
Single venturi nozzle (Hamm type)



Internally rifled nozzle (Spirolet)



Plastic nozzle body with annular water ring and double venturi nozzle (double bubble). To the right is a detail of the annular water ring which eliminates individual holes in the water ring



90-deg nozzle body with tapered nozzle

Fig. 3.14-Miscellaneous nozzle and nozzle bodies

(400 kPa) should be available at the nozzle. High pressure booster pumps with surge tanks to provide uniform flow are utilized for this purpose (Fig. 3.18).

3.8.2 *Water heaters*-For cold weather shotcreting, a water heater may be required to bring the temperature of the mixture above 60 F (15 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*-The best working platform is a stable one that does not move or vibrate. This can be provided with tubular frames, wood scaffolds, personnel lifts, snoopers, and fixed swinging stages. Whatever the working platform, it must meet all applicable safety standards and should be designed not to interfere with nozzle operation.

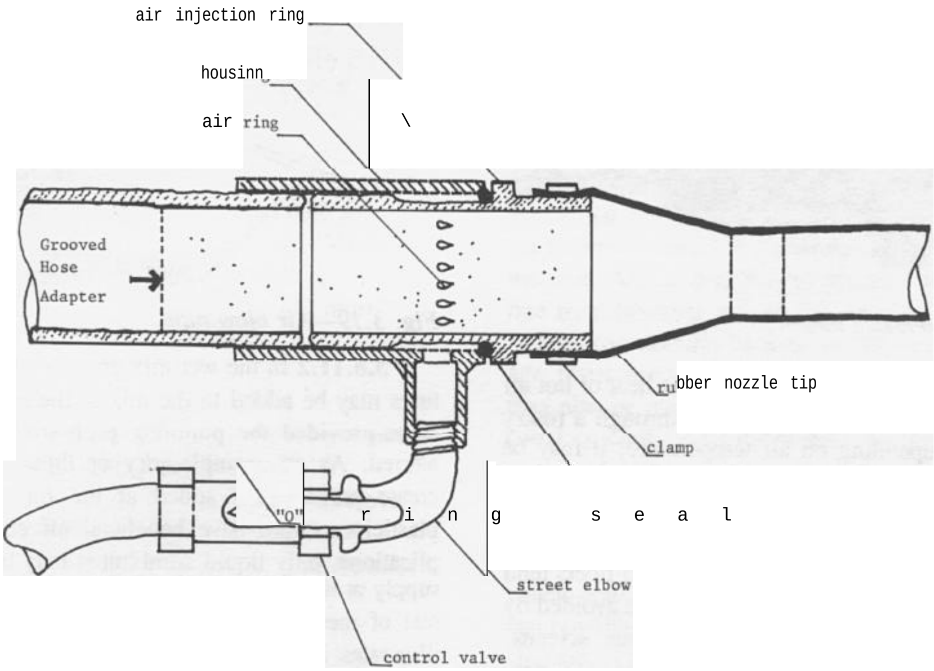


Fig. 3.15-Wet-mix nozzle

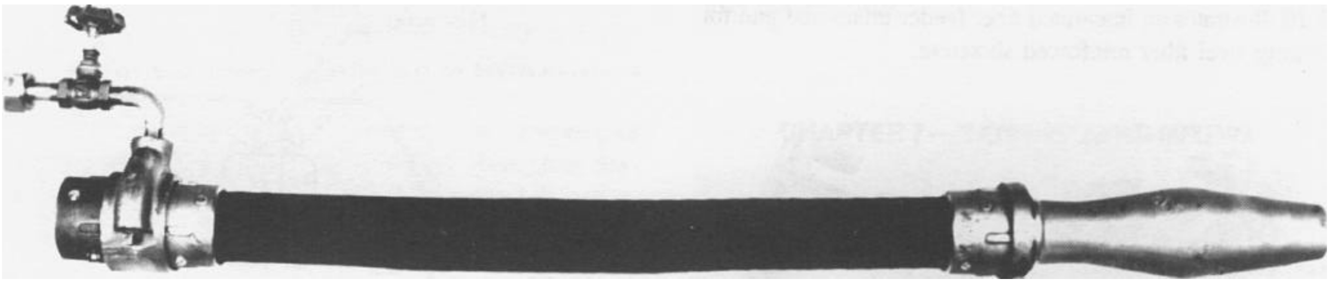


Fig. 3.I6-Hydromix nozzle

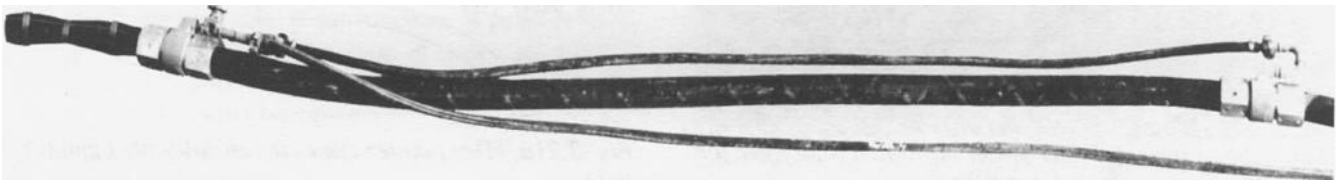


Fig. 3.17-Prewetting "long" nozzle

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 nozzleman from having a clear view of the work. The safety implications also complicate the situation. Adequate ventilation in the form of blowers, fans, and venturi air movers will alleviate the problem.

3.8.5 *Communication devices*-It is imperative that the nozzleman and gun operator be in constant and clear contact throughout the placement operation. When line-of-sight signals are impossible, communication is maintained through the use of sound powered or electric telephones, low voltage bells, or an air whistle.

3.8.6 *Space heaters*-To assure proper and complete hydration of the freshly placed shotcrete, the shotcrete should be cured at temperatures as specified in ACI 306. The use of space heaters that blow uncontaminated heated air, or infrared heaters is recommended. Fuel burning heaters should be vented to prevent carbonation of the shotcrete.

3.8.7 *Lighting*- Since dust and mist affect visibility in confined areas it is usually necessary to use some type of floodlighting. The system should be watertight, reflectors should have lens guards to prevent shattering of the lamps.

3.8.8 *Blow pipes*-A blow pipe is used to help keep rebound, overspray, and loose debris from the advancing work. The blow pipe is usually fabricated from ½ or ¾ in.(12 or 20 mm) pipe approximately *4* ft (1.2 m) long and equipped with a control valve and tapered or flattened exhaust tip (Fig. 3.19).

3.8.9 *Aggregate dryers*-There is occasional need to dry or heat aggregate to be used in the shotcrete mix. This may be accomplished by placing corrugated metal pipe under the

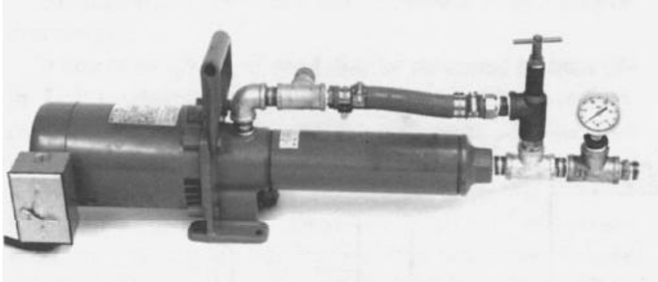


Fig. 3.18-Water booster pump

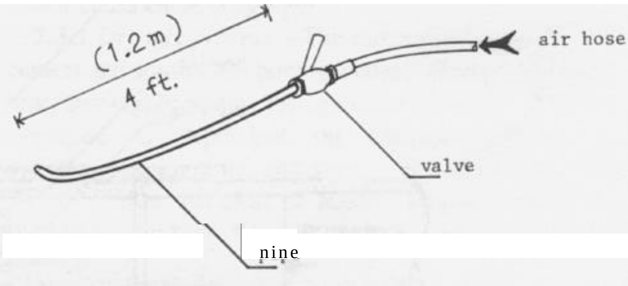


Fig. 3.19-Air blow pipe

aggregate pile and introducing some type of heat or hot air into the pipe or by passing the aggregate through a rotary kiln-type dryer. Depending on air temperature, it may be necessary to cool the aggregate before use.

3.8.10 *Fiber feeders*-When using fibers in shotcrete, they must be uniformly distributed throughout the mix. This may be difficult to achieve since uncollated steel fibers tend to clump or ball. Normally, this problem can be avoided by batch proportioning and the use of appropriate screens. Continuous proportioning equipment may also be used, provided the feeder is carefully synchronized with the mixer. The use of collated fibers reduces "balling" problems. Fig. 3.20 illustrates an integrated fiber feeder mixer and gun for placing steel fiber reinforced shotcrete.

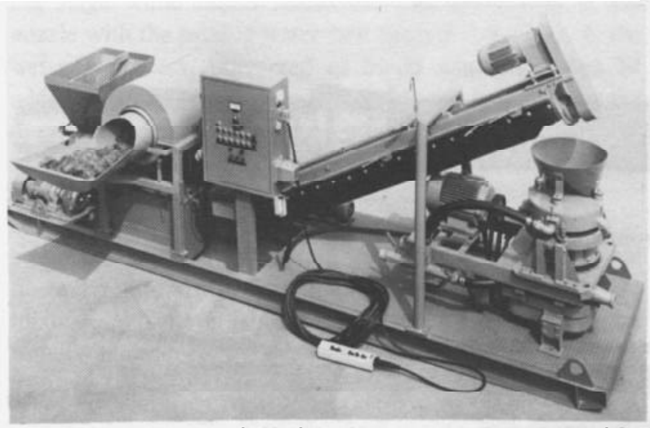


Fig. 3.20-Integrated fiber feeder mixer and rotary gun for installing fiber reinforced concrete

3.8.11 *Admixture dispensers*-Job conditions may dictate the use of an admixture in the shotcrete. Most 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) and whether the placement will be adversely affected.

3.8.11.1 In the dry-mix process, dry (powder) admixtures are usually introduced into the mix at the batching stage. If a continuous feed gun is being used they may also be added directly into the gun hopper by a special dispenser. Fig. 3.21a and 3.21b show an auger-type dry dispenser driven by and calibrated to the gear train of the shotcrete machine.

In the dry-mix process, liquid admixtures must be introduced to the mix at the nozzle through 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. Fig. 3.22 represents the latter case.

3.8.11.2 In the wet-mix process, dry or liquid admixtures may be added to the mix at the batching and mixing stage provided the pumping properties are not adversely altered. As an example, dry or liquid accelerator would create problems if added at the mixer while a superplasticizer might have beneficial effects. In wet-mix applications, only liquid admixtures may be added to the air supply at the nozzle. They are proportioned to the delivery rate of the mixture through the material hose. Fig. 3.22 illustrates a common arrangement of a liquid accelerator system using a pressurized tank. The use of metering pumps is a suitable alternative.

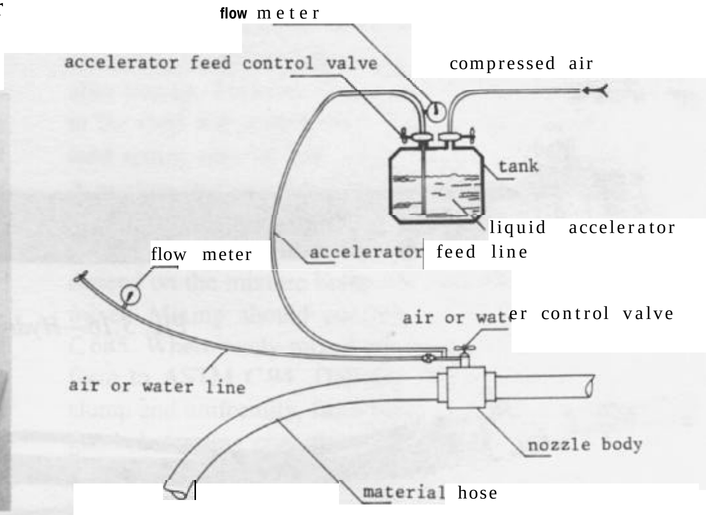


Fig. 3.21a-Dry powder dispenser on calibrated gun (dry-mix)

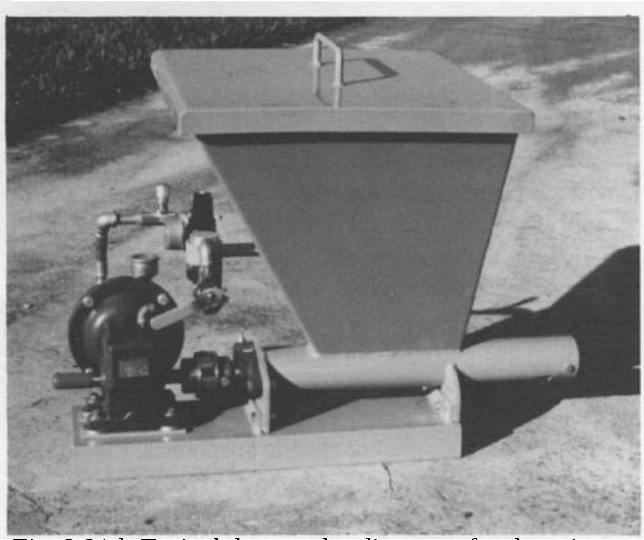


Fig. 3.21 b-Typical dry powder dispenser for dry-mix shotcrete

3.9-Plant layout and operation

3.9.1 *Plant layout*- Proper plant layout is essential for efficient, economical, and successful shotcrete operation. It is important that the equipment be placed as close to the work as possible to minimize the length of 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. A typical plant layout is illustrated in Fig. 3.23.

3.9.2 *Plant operation*-Some key requirements in producing high quality shotcrete on a regular basis are an efficiently organized plant, and properly maintained equipment. It is imperative that each piece of equipment be inspected and cleaned at least on a daily basis. 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 indoctrinate 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-Remote shotcrete equipment

The use of shotcrete for underground support has found widespread acceptance and use in the United States and abroad. With this acceptance has come the development of highly sophisticated equipment utilizing remote controlled and semiautomatic nozzle booms. The operator is set safely back from the face, 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. Fig. 3.24 shows a typical arrangement.

3.11-Modified shotcrete systems

3.11.1 *Gun casting*- The gun casting technique utilizes normal dry-mix equipment except that the nozzle is replaced by a casting head (Fig. 3.14) which is essentially a velocity-reducing device. It permits fine or coarse aggregate mixes to be placed at low velocity similar to pumped concrete. Gun casting almost eliminates rebound and allows large and small volumes of material to be efficiently placed in distant or inaccessible locations (see also Section 1.9.5).

3.11.2 *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 for many applications will do a satisfactory job.

3.11.3 *Pressure grouting*-Some dry- and wet-mix shotcrete machines can be adapted to some types of pressure grouting use. The type of application will determine the feasibility of a particular unit.

3.11.4 *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 are filling the annular space between concentric pipelines, abandoned pipelines and tanks, and the space behind prefabricated tunnel liners prior to grouting.

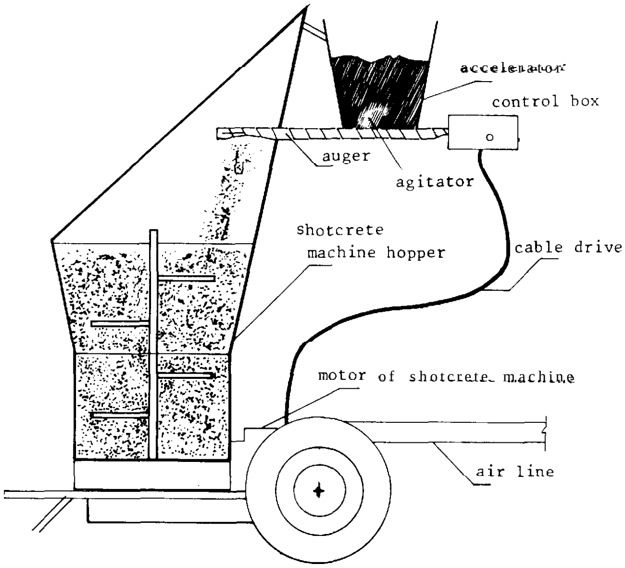


Fig. 3.22-Schematic of liquid accelerator system (wet- or dry-mix)

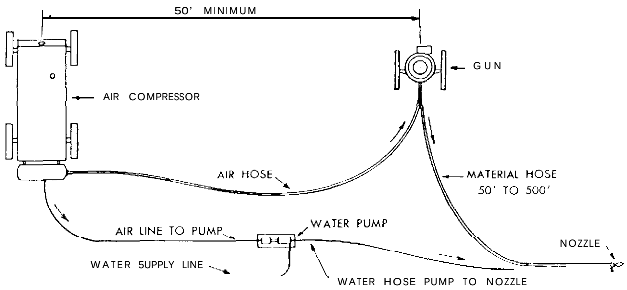


Fig. 3.23-Typical arrangement (plan view) of equipment for shotcreting

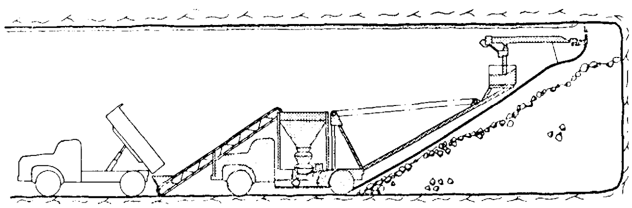


Fig. 3.24-Remote nozzle boom

CHAPTER 4-CREW ORGANIZATION

4.1-Introduction

The most important element in the successful installation of a shotcrete application is the human one, the individuals making up the crew. The shotcreting crew, consisting of competent supervisors and skilled craftsmen, must be trained, integrated, and motivated to provide a team effort that will result 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 the shotcreting application.

4.2-Composition and duties

The basic shotcrete crew may consist of (a) a foreman, (b) a nozzleman, (c) a finisher, (d) an assistant nozzleman, (e) a gunman or pump operator, (f) a mixer operator, and (g) laborers.

Some of these duties may be combined by having one person perform more than one of the above operations. For example, the foreman could also function as the nozzleman; the finisher and assistant nozzleman tasks could be performed by one person; or the gunman and mixer functions could be combined and be performed by one person. On other jobs, more than one nozzleman and finisher may be required and where several crews are operating, a superintendent and/or engineer may be required.

The work of each member of the shotcrete crew, listed above, is directed and coordinated by the foreman so as to obtain a successful application.

4.2.1 *Foreman's duties*-The foreman is responsible for planning and organizing the crew and work, maintaining a safe work place and monitoring quality control procedures. He is responsible for the inspection and maintenance of equipment, as well as ordering and expediting delivery of materials. The foreman sets the pace of the work, maintains crew morale, assures good housekeeping, and acts as liaison to either the general supervision or to the owner's inspection team. He is usually a veteran nozzleman, finisher, and gunman and should be able to fill any of the positions if required.

4.2.2 *Nozzleman's duties*-The nozzleman is the key person in a shotcreting operation and is responsible for application of the shotcrete and for bringing it to required line and grade in a workman-like manner. His duties include coordinating the application with the foreman, finishers, and gunman. Before shotcreting, he must see that all surfaces to be shot are clean, sound, and free of loose material and that anchors and reinforcing and ground wires are properly placed and spaced. During shotcreting, he controls the water content for dry mixes, insures that the operating air pressure is uniform and will provide high velocity at impact for good compaction, and sees that rebound and sag are removed. He provides leadership and direction for the shotcrete crew which aids in his task of shooting good quality shotcrete. He is usually an accomplished finisher and gunman.

4.2.3 *Finisher's duties*-The finisher trims and scrapes the shotcrete, bringing it to line and grade prior to final finishing. He also locates and removes sand pockets, overdry areas, sags and sloughs, and guides the nozzleman to low spots that require filling with shotcrete. He also can stand in for the nozzleman and gunman where necessary. Some applicators combine the duties of finisher and assistant nozzleman on small projects.

4.2.4 *Assistant nozzleman's duties*-The assistant nozzleman (nozzleman helper) helps the nozzleman by dragging hose and performing other duties as directed by the nozzleman. He relays signals between the gunman and nozzleman and may also relieve the nozzleman for short rest periods. He operates the blowpipe, if one is required, to keep the areas in advance of the shotcrete free of dust and rebound. The assistant nozzleman may be an apprentice nozzleman who has had gunman experience.

4.2.5 *Gunman's duties*-The gunman is responsible for providing a constant flow of properly mixed material to the nozzleman. He is responsible for operating and maintaining a clean shotcrete machine and assisting in assuring quality control. He is particularly attentive to the needs of the nozzleman and sees that the mix is properly prepared. He 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. He positions and moves the material hose or hose boom if and when required. He is responsible for cleaning and maintaining the material hose and pump. He 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, he is responsible for storage, care, and accessibility of the materials. He sees that the mixture is free of extraneous materials and lumps, and that the aggregates have the proper moisture content. He insures a constant flow of shotcrete but is also careful not to mix more material than can be used within the specified time limits. He supervises the laborers who are supplying and loading the mixer.

4.2.8 *Laborer's duties*-The laborer's duties include moving of equipment, hoses, scaffolding, and materials. They are responsible for housekeeping, maintaining clean work areas, removing rebound and overspray and, in general, provide support for the shotcrete application.

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 his crew should give evidence prior to employment that each has performed satisfactory work in similar capacities for a specified period.

4.3.2 *Foreman-The* foreman normally has proficiency at all crew positions and should have a minimum of 3000 hr experience.

4.3.3 *Nozzleman*-The nozzleman should have certification (refer to ACI 506.3R) or a minimum of. 3000 hr experience as a nozzleman and completed at least one similar application as a nozzleman. He should also be able to demonstrate, by test, his ability to satisfactorily perform his duties and to apply shotcrete as required by specifications.

4.3.4 *Finisher*-The finisher should have shotcreting experience; however, if his work provides the specified result, this should qualify him for the position.

4.3.5 *Gunman*-The gunman should be familiar with and 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, he should have at least one year's experience as a gunman.

4.4-Communications

Communication plays a vital role during the shotcreting application. Because of many factors, such as the distance between the nozzleman and gunman, objects obstructing their view of each other, and noise levels that prevent oral communications, the shotcrete crew must decide on a communication system.

4.4.1 *Communication methods*-Several methods of communications are used within the industry. A practical method is finger signals. A common practice is to have the nozzleman or assistant nozzleman hold up one or two fingers in view of the gunman, indicating that he should regulate either the air pressure or material feed, respectively. Other signals may be used by individual companies and normally are customized to individual preference. Hand or air motions and other methods of communications, such as whistles, two-way radios, or sound-powered telephones 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 the signals must be understood by each crew member to insure a safe and proper application.

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 prior to 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 structural integrity of the receiving surface.

5.2-Surface preparation

The surface preparation required depends on the condition and nature of the surface against which shotcrete is to be placed. In the following sections special requirements of surface preparation for earth, steel, concrete, masonry, rock, and wood surfaces will be discussed.

5.2.1 *Earth surfaces*-The range of shotcrete applications covering earth surfaces is extremely broad and includes, but is not limited to, 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 assure the design thickness of the shotcrete. Shotcrete should not be placed on an earth surface which is frozen or spongy. To prevent excessive absorption of mixing water from the shotcrete, the following techniques are available:

5.2.1.1 Prewetting of the earth surface by water spray prior to 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.

5.2.1.2 A moisture barrier system may be installed which will inhibit the movement of moisture from the newly placed shotcrete into the earth. If sheet material is utilized, care must be taken to avoid wrinkling or folding to eliminate the formation of voids beneath the moisture barrier.

5.2.2 *Steel surfaces*-Before shotcrete is applied over steel surfaces all traces of loose mill scale, rust, oil, paint, or other contaminants should be removed by sandblasting or other methods. The condition should be as set forth in SSPC-SP6.6.

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

5.2.3 *Concrete surfaces*

5.2.3.1 It is imperative to completely remove all sgalled , severely cracked, deteriorated, loose, and unsound concrete from the existing concrete surface by chipping, scarifying, sandblasting, water blasting, or other mechanical methods. Any concrete which is contaminated by chemicals or oils should be removed by chipping. 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. If saw cutting is impractical, the edges are chipped with a slight taper toward the center of the repair area. Feather edging should be avoided,

5.2.3.2 If pneumatic or electric impact tools are employed to accomplish removal they should be chosen to minimize damage to sound concrete which 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.

5.2.3.3 Following initial removal, the surface of the existing concrete should be inspected to ascertain 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.

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

5.2.4 *Masonry surfaces*-Masonry surfaces require preparation similar to that of concrete surfaces; however, the problem of preventing absorption of water from the shotcrete into the underlying masonry is critical. Severe cracking of the shotcrete can result. One method used to prevent this problem is dampening the surface.

5.2.5 *Rock surfaces-* Loose material, debris, chips, mud, dirt, or other foreign matter must be completely removed to assure a strong bond between the rock and the shotcrete. However, there may be situations 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 the bond between shotcrete and the form. 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, or expanded metal lath (Fig. 5.1). In all cases, the form must be adequately braced and secured to prevent excessive vibration or deflection during the placement of the shotcrete. All formwork must 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. 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 will occur under the dead load of the fresh shotcrete.

5.4-Reinforcement

5.4.1 General-Reinforcement consisting of welded wire fabric (mesh) or plain or deformed reinforcing bars is required in installations where shotcrete is 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

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

repair where bar reinforcing may already exist, reinforcement in the form of welded wire fabric (mesh) is recommended. Wire fabric limits the development and depth of cracking resulting from shrinkage and temperature stresses.

Properly anchored mesh can prevent or retard future peeling of the shotcrete layer as a result of debonding in service. Debonding may be caused by poor or nonuniform bond, deterioration of the substrate, or overload, among other influences. Well designed shotcrete which is properly placed against a structurally sound substrate should not debond at the interface.

Combinations of small bars and mesh arc used where mesh alone would not be structurally sufficient for the application, and where uniform spacing and cover are critical as in curved and irregular surfaces. Bars also aid in limiting deflection of the mesh during its installation and flexing during the shotcreting operation. A suitably designed combination of bars and mesh can also reduce the number of layers of mesh required for thicker sections.

Reinforcing bars are rarely used in shotcrete with a thickness less than 1½ in. (40 mm). Mesh may be used in thicknesses down to ¾ in. (20 mm). For thin sections of shotcrete, properly sized steel fibers may be successfully substituted for standard reinforcement.

The soundest shotcrete is usually obtained when the reinforcement is designed and positioned to cause the least interference with the placement of the shotcrete. Good practice dictates that small bar sizes be used, with #5 (No. 15M) bar being the maximum size. If larger sizes are required by the design, exceptional care must be taken to properly encase them with shotcrete. Welded wire fabric is usually galvanized with a minimum wire spacing of 2 in. (50 mm) in either direction. In any case, reinforcement should be sized, spaced, and arranged to facilitate the placement of shotcrete and minimize the 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 removed. If possible, clearances around an exposed bar should be at least three times the maximum size of the largest aggregate particle in the shotcrete mix.

Reinforcement should be rigidly secured in the position shown on the job drawings with sufficient ties to prevent its movement or deflection. Loose mill scale and rust and oil or other coatings that can reduce the bond of the shotcrete to the reinforcement should be removed.

5.4.2 *Bar reinforcement-*Where possible, bars should be spaced to permit shooting at a slight angle from either side of the bar. If the design allows, lapping of the reinforcing splices should be avoided. Lapped bars should be spaced apart at least three times the diameter of the largest bar at the splice. For most shotcrete applications with thicknesses less than 8 in. (200 mm), one layer of reinforcing is usually sufficient with or without mesh depending on the application. For greater thicknesses utilizing several layers of bars, the size and spacing of the bars must be carefully designed and installed for proper and effective shotcreting of deeper recesses. Where several layers of reinforcing are in place prior to shotcreting, the outermost layers should be sufficiently open to allow the nozzle clear, unobstructed access to the interior of the member (Fig. 5.1).

All intersecting reinforcing bars should be rigidly tied to one another and to their anchors with 16 gage (1.6 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.

5.4.3 *Fabric reinforcement*--Some commonly specified welded wire fabric sizes are listed in Table 5.1.

Other sizes may be used depending on the application and its design. The mesh should be cut to proper size and carefully bent so as to closely follow the contours of the areas to receive shotcrete (Fig. 5.2). The reinforcing mesh should be securely tied with 16 gage (1.6 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 one and one-half spaces in both directions, and be securely fastened. When more than one layer of mesh is required, the first layer is covered with shotcrete before placing the second layer. Some type of anchor or tie should extend to the second layer. Current practice requires at least one layer of mesh for every 3 in. (75 mm) of shotcrete. Unless the design dictates otherwise, the sheet of mesh is placed in the center of the shotcrete layer. When mesh and bars are used together in combination, the mesh is placed exterior to the bars.

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, shotcrete thickness, nature of the original surface, and type, weight, and geometry of the reinforcement. The maximum recommended spacing of anchors for most applications is: Floor surfaces, 36 in. (900 mm) on centers both ways (o.c.b.w.); Vertical and inclined surfaces, 24 in. (600 mm) o.c.b.w.; Overhead surfaces, 18 in. (450 mm) o.c.b.w. 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 to permit proper cover and its complete encasement with sound shotcrete.

5.5.1 *Anchoring to steel*-Reinforcement may be attached to steel surfaces using mechanical clips, blank nuts welded to the steel, stud welded devices, slab bolsters, or by direct attachment. Clips and bolsters are only used to directly attach mesh to steel. Studs or nuts may be used to attach reinforcing bars or mesh. Drilling holes through structural members to facilitate the anchoring of reinforcing should be avoided.

TABLE 5.1-WELDED WIRE FABRIC SIZES

Old designation	New designation
2 X 2 in./12g X 12g	2 x 2/W0.9 x W0.9
3 X 3 in./10g X 10g	3 x 3/W1.4 x WI.4
4 X 4 in./ 8g X 8g	4 x 4/W2.1 x W2.1
6 X 6 in.1 6g X 6g	6 x 6/W2.9 x W2.9
6 X 6 in./10g x 10g	6 x 6/W1.4 x WI.4

Fig. 5.2-Gunning through welded wire fabric cut and bent to follow contours of repair

5.5.2 *Anchoring to concrete, masonry, or rock*-Reinforcement may be attached to concrete, masonry, and rock surfaces using expansion anchor bolts, steel dowels, powder activated studs, self drilling fasteners, and expansion shields. Epoxies or other adhesive systems may also be used. The choice depends to a great degree on the application, type of reinforcement specified, 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 followed explicitly.

The most commonly used anchors for concrete fastening are expansion anchor bolts. They come 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 thicknesses of shotcrete from 1 ½ to 6 in. (40 to 150 mm).

Powder actuated studs are useful for thinner uniform sections where large numbers of anchors are required and loads are light. Self-drilling fasteners and expansion shields are used to a lesser extent but are useful for thick, nonuniform shotcrete sections, 6 in. (150 mm) and up, and where multiple layers of reinforcement are specified.

Steel dowels or reinforcing bars are used in structural shotcrete applications where sections are thick, 6 in. (150 mm) and up, 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 grout.

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. If the wood surface is a removable form, nails should not be used and the chairs and bolsters should be be plastic tipped to eliminate rust staining 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).

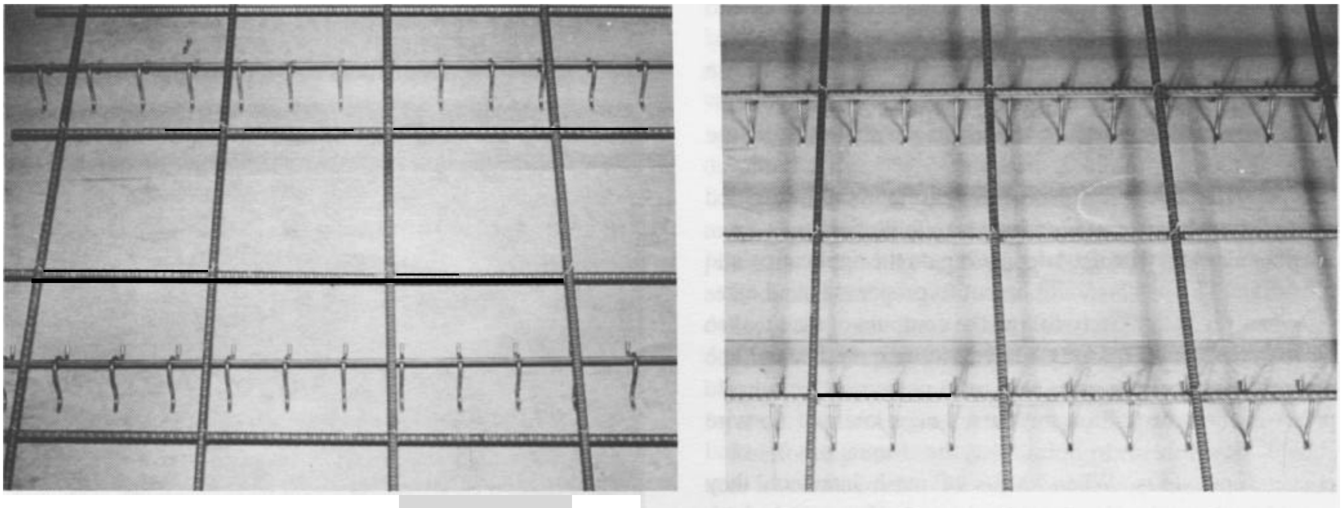


Fig 5.3-Positioningn slab bolsters. Correct (left) and incorrect (right) method for placing continuous chairs orr sllab bolsters. (To avoid sand pockets, the bolster wire should not be adjacent or parallel to a mesh wire)

5.6-Alignment control

Alignment control is necessary to establish line and grade in shotcrete construction and to insure that proper and uniform material thickness and cover are maintained. Alignment control is accomplished by the use of ground wires, guide strips, depth gages, depth probes, or conventional forms.

5.6.1 *Ground wires*-Ground wires consist of 18 or 20 gage (1 or 0.8 mm) high strength steel wire called "music" or "piano" wire combined with a device, usually a turnbuckle or spring coil, that places the wire under suitable tension. They are the most convenient means to establish line and grade where forms are used for backup purposes. Wires may be used individually to establish comers 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).

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 (0.6 to 0.9 m) 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 comer of the guide strips.

5.6.3 *Depth gages*--Depth gages are small metal or plastic markers attached to or installed perpendicularly in the substrate or backup material at convenient intervals and heights, They provide a preset guide to the thickness of the shotcrete and are positioned just below the finish coat of shotcrete. They are left in place provided they do not affect the integrity of the application (Fig. 5.5).

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 steel, 12 to 14 gage, and

Fig. 5.4-Gunning shotcrete using ground wires as a guide to bring materials to line and grade

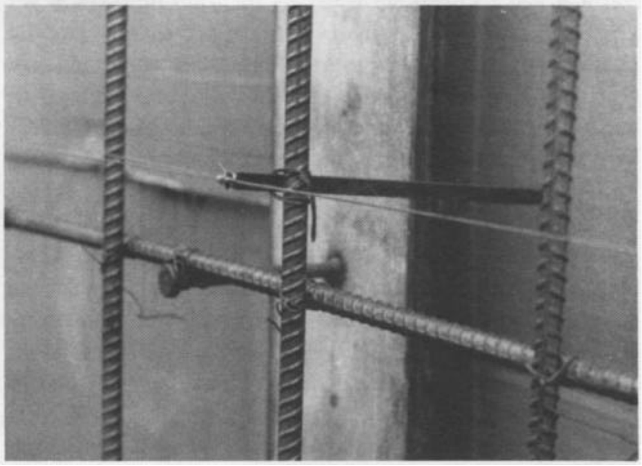


Fig. 5.5-Ground wire attached to depth gage which is tied to reinforcing steel and will be left in place

marked with the specified shotcrete thickness. Probes are inserted into the shotcrete until the substrate is reached indicating the depth of shotcrete. They should only be used if puncture holes can be tolerated in the lining.

5.6.5 *Formwork*-The use of conventional forms in shotcrete work is the exception rather than the rule; however, when they are used, they usually provide automatic alignment control eliminating special devices for line and grade. Nozzle technique must be carefully controlled to avoid sand pockets and other defects.

5.7-Joints

5.7.1 *Contraction joints*-Contraction joints may be provided by the prepositioning of full thickness strips, usually wood or steel, which are left in place, or by saw cutting the shotcrete shortly after it has achieved its final set. The spacing of contraction joints 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 10 m).

5.7.2 *Construction joints*-Square construction joints are generally avoided in shotcrete construction because they form a trap for rebound. However, where the joint will be subjected to compressive stress, square joints are commonly required, in which case the necessary steps must be taken to avoid or remove trapped rebound at the joint. The entire joint should be thoroughly cleaned and wetted prior to the application of additional shotcrete.

Where a section of shotcrete is left incomplete at the end of a shift some provision must be made to assure the joint will not develop a plane of weakness at this point. The joint is therefore tapered to an edge, usually about one-half 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 laid flat.

5.8-Protection of adjacent surfaces

5.8.1-Rebound, overspray, and dust resulting from the shotcrete application can damage adjacent structures, equipment, and grounds. This problem is especially aggravated on windy days. It is therefore very important to evaluate the effect of the shotcrete application on adjacent surfaces and make the necessary arrangements to protect them.

5.8.2-Ideally, this protection can be effected by isolating the shotcrete operation from areas that could be affected. This is not always possible and protection can take the form of cover, masking materials, or temporary protective coatings. Cover 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.

5.8.3--If none of the above are practical, adjacent surfaces should be cleaned and washed before the overspray hardens.

5.8.4-The protection of adjacent surfaces should include concern for the buildup of overspray, rebound, and dust on surfaces which are to 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

The design of mix proportions for shotcreting is usually based on 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 nozzleman 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 utilizing thin layers of shotcrete, properties other than compressive strength may be more important for a successful application. Such qualities as permeability and durability may have to be considered, thereby 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 undertaking to proportion a mixture, the following should be considered:

(1) Preferred characteristics of the shotcrete work and the constraints involved

(2) The type of specification selected for the work, performance, or prescription

(3) The type of shotcrete placing equipment appropriate for the work-wet- 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.

6.2.1 *Performance specification*-The performance specification states the required quality of shotcrete, and the applicators must decide how it can be achieved.

Typically, these properties might be specified:

(1) Cement type

(2) Aggregate gradation

(3) Compressive strength at specified age

(4) Slump, if wet mix

(5) Air content, if wet mix

(6) Specific performance requiring use of admixtures

It is common in many applications to specify compressive strength only.

It is strongly recommended that mixture proportions be determined as part of the preconstruction test program.

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

(1) Cement type and content
(2) Aggregate gradation, weight, or volume
(3) Admixtures and dosage
(4) Slump, if wet mix
(5) Air content, if wet mix

This type of specification is frequently simplified by specifying cement-aggregate proportions such as 1:4.

It is recommended that a performance specification be used whenever possible. It is also recommended that, where possible, the installer be consulted on the types of cement, aggregate, and shotcrete equipment available and the shotcrete properties that can be practically achieved.

6.3-Proportioning of shotcrete mix

6.3.1 *General*-Many of the principles of normal concrete technology can be applied to shotcrete, particularly the wet-mix process. However, differences must be recognized before proportioning mixtures. In-place shotcrete has a higher cement factor than the design mixture due to rebound. Rebound also eliminates a large percentage of coarse aggregate resulting in finer aggregate in place. This effect plus the fact that the cement content of shotcrete mixtures is usually higher than in conventional concrete, increases the possibility of shrinkage problems and the development of surface cracking. This situation is less critical in wet-mix shotcrete than in the dry-mix process.

It is not practical to conduct laboratory trial mixes for the dry-mix process and there are even problems in duplicating as-shot conditions for wet-mix process. Therefore, field trials and preconstruction testing as described in Section 6.4 may be necessary for mixture qualification.

6.3.2 *Wet-mix process*--Proportioning can basically be done in accordance with AC1 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.

The slump of the wet-mix process shotcrete should generally be the minimum that can be handled by the pump. A slump range of 1 ½ 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.

Wet-mix shotcrete can be air entrained. A range of 5 to 8 percent of total air at the pump is generally desirable.

There will be loss of both slump and entrained air through the pump. These losses are normally in the order of ½ to $1^1/2$ percent air and ½ to 1 in (12 to 25 mm) slump, although the losses vary with length of line, type of pump, and initial levels of air. Additional entrained air is lost during gunning as indicated in Section 2.7.2.

6.3.3 *Dry-mix process*

6.3.3.1 *Aggregate proportion.* Aggregrates should be a blend of sizes as required to produce a combined grading within the limits of Table 2.1.

The particle size distribution of aggregates in place will be markedly finer than when batched because the larger particles have proportionally larger rebound loss. Table 6.1 contains typical data for a fine aggregate dry-mix shotcrete with optimum nozzle velocity and average rebound.

TABLE 6.1-TYPICAL CHANGE IN RATIO OF CEMENT TO AGGREGATE PROPORTIONS WITH SHOOTING (REFERENCE 7)

Nominal mix entering gun	Mix in place
1 : 3.0	1 :2.0
1 : 3.5	1 : 2.8
1 : 4.0	1 : 3.25
1 : 4.5	1 : 3.6
1 : 5.0	1 : 3.8
1 : 6.0	1 : 4.1

6.3.3.2 *Mixture proportions.* There is no recognized rational method of designing dry-mix shotcrete proportions for strength. Applicators from one geographical area, who use the same consistent sources of materials, can provide adequate proportioning data from prior experience. 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. Results to 12,000 psi (80 MPa) compressive strength 2 have been reported for trial mix panels and 10,000 psi (70 MPa) are commonly quoted in the literature. Strengths higher than 5000 psi (35 MPa) should not be specified except in carefully controlled projects where research into the potential performance of local materials has been done.

For coarse aggregate shotcrete mixes, Table 6.2 illustrates some typical data on the effect of cement content on strength.

Trials are required to determine the final cement contents. The method of evaluating the strength of shotcrete is detailed in ACI 506.2.

TABLE 6.2-STRENGTH VERSUS CEMENT FACTOR

Specified 28-day compressive strength		Cement factor	
psi	MPa	lb/yd³	kg/m³
3000	21	500-650	300-380
4000	28	550-700	325-425
5000	35	650-850	380-500

Data is for typical dry-mix shotcrete mixtures.

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

Specified requirements:

28-day compressive strength	-4000 psi (28 MPa)
Maximum size aggregate	— ½ in. (12 mm)
Cement, Type I	

Preliminary design:

Assume in-place density	— 145 pcf moist
Therefore total weight per cubic yard = 145 x 27	-39 15 (2320 kg/m^3)
Select cement content as	-650 pcy (385 kg/m^3)
Estimate water-cement ratio as	-0.35*
Therefore water required is	-230 pcy (135 kg/m^3)

Aggregate content

(stone + sand) = 3915 – 650 – 230	-3035 lb for 1 y^3
(= 2320 – 385 – 135)	-(1800 kg for 1 m^3)

To this, a correction for surface moisture in aggregate (usually about 3 percent) must be added. Admixture dosages have not been included. Refer to Section 2.7.

6.4-Preconstruction testing

For preconstruction studies, test panels simulating actual job conditions provide a sufficiently reliable indication of the quality to be expected in the structure. A panel is fabricated by gunning onto a back form of heavy plywood or steel plate. A separate panel should be fabricated for each mixture proportion being considered, and also for each shooting position to be encountered in the structure, down, horizontal, and overhead.

The mixture proportions should be overdesigned to produce sample strengths higher than the design strength. Refer to ACI 2 14 for guidance.

At least part of the panel should contain the same reinforcement as the structure, to show whether sound shotcrete is obtained behind reinforcing bars. The panel should be large enough to indicate what quality and uniformity may be expected in the structure; generally it should be not less than 30 in. (750 mm) square. The thickness should be the same as in the structure except that it should normally be not less than 3 in. (75 mm).

Cubes or cores should be obtained from the panels for testing. Cores should have a minimum diameter of 3 in. (75 mm) and an *L/D* of at least 1. The specimens should be tested in compression at the required ages. Core strengths should be corrected for *L/D* as described in ASTM C 42

Cube strengths may be reported as determined, or converted to cylinder strengths by multiplying by the factor 0.85.

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

Tests for modulus of rupture, absorption, drying shrinkage, resistance to freezing and thawing, and other properties may also be made if desired, using appropriate specimens cored or sawed from the panel.

The procedures described above should determine the optimum proportions to achieve the result desired. Once the mix proportions have been established they should be monitored. However, it may be permissible to make the test panels concurrently 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, mix proportions, equipment, and personnel have given satisfactory results on previous work, these preliminary studies may not be justified.

*For coarse aggregate, dry-mix shotcrete water-cement ratios range from 0.30 to 0.40.

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 but weight batching is preferable. However, 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 in common use in some areas. It is also possible to use preblended dry cement and aggregate for dry-mix. This must be predampened before being introduced to the shotcrete delivery equipment.

In volumetric batching, sand bulking can cause a major error in the proportions. It is necessary to check for bulking by periodically monitoring the bulk density, usually on a daily basis.

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 higher values. It is recommended that the Tolerances in ASTM C 94 be increased to

(1) Cement: plus or minus 2 percent of mix proportion weights

(2) Aggregate: plus or minus 4 percent of mix proportion weights

(3) Admixtures: plus or minus 6 percent of mix proportion weights

In lieu of weighing, cement may be measured by bags (94 lb. U.S.), while the aggregates may be batched volumetrically, provided weight checks are made as described above. Weight batching can be accomplished at a central ready-mixed concrete plant or near the job site. Volumetric batching equipment such as that associated with mobile mix units are available for high production work (see Section 3.5.2). A less convenient method for field batching utilizes wheelbarrow scales. Weight calibrated containers may also be used to manually proportion mixes.

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 6 percent. The sand should be dried or wetted as required to bring the moisture content within that range. Large fluctuations in moisture content should be avoided.

7.2.1 *Admixtures*-Admixtures for shotcrete are available in either powder or liquid form or both. The method of introducing the admixture 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 (see Section 3.8.11.1). In the wet-mix process, powdered or liquid admixtures can be added at the batching stage or liquids can be added at the nozzle in the air supply using a proportioning device. Rapid set accelerators are only introduced at the nozzle in the wet-mix process (see Section 3.8.11.2).

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

7.2.2 *Prepackaged material*--Occasionally, situations arise where access is poor and/or small volumes of shotcrete are required and logistics do not indicate using bulk materials. The cement, aggregates, and sometimes fibers can be dried, weighed, and prebagged. Dry mixtures should be predampened and mixed before use.

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 avoid lumps of material, oversized aggregate, and other foreign objects which could cause plug-ups.

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 visible indication of thorough mixing is the absence of color variation (sand streaks) in the mixture. Vibratory screening of the shotcrete mix on exit from the mixer tends to reduce the presence of these streaks, though it is not a cure-all for poor mixing practice. Sand streaks should be avoided since 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 mix 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 and is usually light gray. 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 mix.

For optimum strength and setting time a shotcrete mixture containing damp sand should be gunned as soon as possible 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 become 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 304 and ASTM C 685. Where ready-mixed 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 to a good shotcreting operation, especially in vertical and overhead applications. A mix that becomes difficult to pump should be discarded; otherwise, a batch should be gunned within the time specified in ASTM C 94.

Reuse of discarded shotcrete material should not be tolerated.

CHAPTER 8-SHOTCRETE PLACEMENT

8.1-Introduction

The importance of using proper placement techniques to insure quality shotcrete cannot be overstated. This chapter represents the best current practice; however, it should be understood that practice varies geographically and that acceptable variations may exist. The information contained herein is provided to supply guidance and direction to the owner, designer, applicator, inspector, and other interested parties. Supplementary information and procedures to aid in achieving the desired result may be found in ACI 506.2.

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 since much of the information it contains complements the subject of shotcrete placement.

8.2-Special applications and mixes

From the standpoint of construction, quality, utility, and cost, shotcrete is best suited to thin, lightly reinforced sections under 6 in. (150 mm). However, there are an ever-increasing number of situations where much heavier sections are being shotcreted. Placement procedures for heavy structural members are discussed in Section 8.5.9

In addition, shotcrete is sometimes required to have special properties such as low unit weight, insulating qualities, or resistance to heat or acids. These may dictate the use of special aggregates, cements or admixtures.

Lightweight aggregate mixtures are being gunned in increasing quantities for wall and floor construction. As in the case of regular aggregates, lightweight shotcrete is best adapted to thin, rather lightly reinforced sections.

Shotcrete is frequently employed for fireproofing structural steel members, and lightweight aggregates are sometimes used in the mixture. The shotcrete also strengthens the members and can be included in calculations of gross concrete section.

Calcium aluminate (high alumina) cement is preferred over portland cement for certain applications where rapid hardening 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 mixes 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 Special Publication No. 57.

8.3-Preliminary procedures

8.3.1 *General*-Prior to starting shotcrete placement, it is important to see that materials and shotcrete equipment are both ready to insure 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 4 to 6 percent, to minimize dusting. Predampening of the aggregate may be required, though too much moisture can cause plugging of the material hose during shotcreting. Material supplied from a centrally located ready-mixed concrete plant may be used if the mix can be used within 45 min* of the time of mixing, and preconstruction testing determines the product meets design strengths. Allowing damp sand to remain in contact with the cement for prolonged periods will result in reduced strength and set retardation (see Section 7.3.1).

Materials for the wet-mix method should meet the requirements of ACI 304.2R.

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

8.3.3 *Equipment*-Proportioning, mixing, and gunning equipment must be clean to insure quality shotcrete. Proportioning equipment should be checked regularly to be certain that the proper mix is being obtained. From an economic standpoint, it is in the applicator's interest to have his equipment in excellent operating condition to maximize production and minimize slow downs, breakdowns, and plugups (hose blockage).

8.3.4 *Cleaning and prewetting*-Surface preparation, as outlined in Section 5.2, may occur days or weeks before the shotcreting operation. If so, the substrate must be recleaned by washing it down with water just prior to shotcreting. In the dry-mix process this is accomplished with an air-water blast from the nozzle.

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

8.4-Gun operating procedures

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

8.4.1 *Dry-mix method*-When starting up, the gun operator introduces only compressed air into the delivery hose, slowly adding mix material at the direction of the nozzleman. The air and material flow must be balanced by the gunman so as to provide a steady, uninterrupted flow of material from the nozzle. The nozzleman 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 blows clear, shutting off the water and then the air.

8.4.2 *Wet-mix method*-Premixed concrete or mortar with a slump, generally between 1 ½ and 3 in. (38 mm to 75 mm) is fed to a remixer on the shotcrete machine. The mix is then pumped to the nozzle where compressed air is added to increase exit velocity and provide a spray pattern. The nozzleman controls the air flow; but water content and consistency are controlled at the mixer. As in the dry-mix method, the flow and volume of material is controlled by the gun operator; however, response time is longer and, therefore, control is not as instantaneous. Starting and stopping procedures are simpler.

8.5-Application of shotcrete

8.5.1 *General*-The quality of shotcrete application depends to a large extent on the gun operator and nozzleman, control of mixing water, nozzle velocity, and nozzle tech-

* For hot weather shotcreting, 15 min would be the limit. (Section 8.8).

nique. In each case, the expertise and experience of the responsible crew member determines the adequacy and quality of operation.

8.5.2 *Gun or pump*-In the dry-mix method, proper gun operation is critical to insure a smooth, steady flow of material through the hose and nozzle. If a suitable balance of air and material flow is not maintained, slugging, plugups, or excessive rebound may occur. Pulsating and intermittent flow of shotcrete material causes under- or overwetting the mix and requires the nozzleman to quickly adjust the water, manipulate the nozzle, direct it away from the work, or stop. Unsuitable shotcrete resulting from slugging should be removed.

In the wet-mix method, slugging does not affect the shotcrete quality to any extent and reliance on the pump operator is not critical. The pump operator should regulate the pump to evenly deliver the wet mix shotcrete at the rate required for the particular shotcrete application and also monitor the concrete being delivered to the pump hopper for correct consistency. The pump operator should also position and move the material hose boom on those jobs which may require a boom pump.

8.5.3 *Control of mixing water*-In the dry-mix method just enough water is added at the nozzle so that the surface of the in-place shotcrete has a slight gloss. The nozzleman can change the water content instantaneously by as little or as much 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, creates sand pockets, makes finishing difficult, and can produce weak and laminated shotcrete. For effective water control, the water pressure at the nozzle should be 15-30 psi (100 to 200 kPa) or more over the air pressure.

The same gunning principles apply for wet-mix shotcrete as for dry-mix as described above, except that the nozzleman has no control over the water content. The slump of the mix is usually held between 1½ and 3 in. (38 and 75 mm). Below a 1½ in. (38-mm) slump, rebound becomes more pronounced while slumps above 3 in. (75 mm) may develop sagging, puddling, or dropouts.

8.5.4 *Nozzle velocity*-The velocity of the material at impact is an important factor in determining the ultimate properties of the shotcrete. For most applications where standard nozzle distances of 2 to 6 ft. (0.6 to 1.8 m) are used, material velocity at the nozzle and impact velocity of the material particles are almost identical. At longer nozzle distances they may differ and it may be necessary to increase the nozzle velocity so that the impact velocity will suit the requirements of the application. Consideration must also be given to the fact that increasing velocity means increasing rebound.

In dry-mix shotcrete with given delivery equipment, 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 rate it is being gunned. These factors allow for great flexibility and versatility in that 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 nozzleman.

The water content in wet-mix shotcrete is predetermined by the type of application and the limitations of workability required for pumping. This limits the use of this method to applications with low and medium velocities and large volume and flow.

Wet-mix shotcrete methods will normally out-produce dry-mix.

8.5.5 *Nozzle technique and manipulation*-Nozzle technique for wet and dry-mix methods is generally similar, requiring considerable attention to detail. Since the capabilities of wet and dry procedures and equipment are different, each requires a somewhat different expertise from the nozzleman. It should not be assumed that the nozzle techniques are exactly interchangeable, especially the finer details of the art.

8.5.6 *Thickness and work position*-Shotcrete may be applied in layers or in single thickness, depending on the position of the work. Overhead work is gunned in layers just thick enough to prevent sagging or dropouts, usually 1 to 2 in. (25 to 50 mm) at a time. Vertical surfaces may be applied in layers or a single thickness, while horizontal or flat surfaces are usually gunned in a single thickness. In any case, thickness of a layer is governed mainly by the requirement that the shotcrete should not sag. Sags or sloughs that go undetected or are not cut out can hide internal cracks and hollows which make the shotcrete vulnerable to water penetration, freeze-thaw action, and reduction in or loss of bond between layers.

8.5.7 *Gunning*-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 nozzleman should direct it away from the work until it again 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 more than 45 deg from the surface (Fig. 8.1 a and 8.1 b). When the nozzle is held at too great an angle from the perpendicular, the shotcrete rolls or folds over, creating an uneven, wavy textured surface which can trap rebound and overspray. This process, known as "rolling" is not a recommended nozzle technique, is wasteful of material and may create porous and nonuniform shotcrete. Angle shooting should only be allowed when no other suitable alternative exists.

To uniformly distribute the shotcrete and minimize the effect of slugging, the nozzle is directed perpendicular to the surface and rotated steadily in a series of small oval or circular patterns (Fig. 8.2). Waving the nozzle quickly back

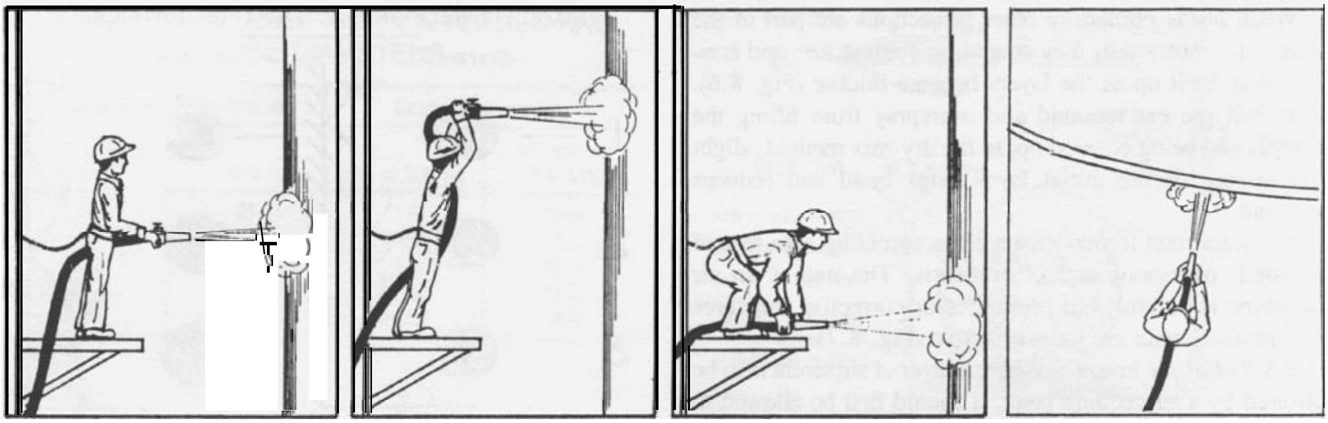


Fig. 8.1a-Gunning positions

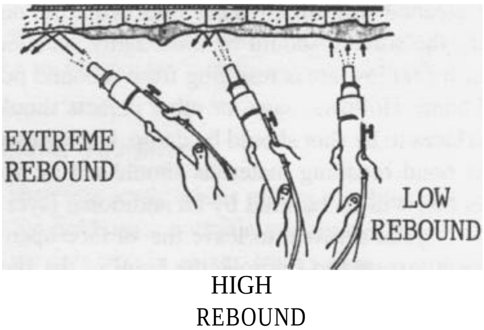
Fig. 8.1b-Correct gunning position-Nozzle perpendicular to receiving surface

and forth changes the angle of impact, wastes material, increases overspray, and unnecessarily increases the rough texture of the surface.

When shooting through and encasing reinforcing bars the nozzle, should be held closer than normal and at a slight upward angle to permit better encasement of horizontal steel and minimize the accumulation of rebound (Fig. 8.3). Also, the mix should be a little wetter than normal, although not so wet that material will slough behind the bar. This procedure forces the plastic shotcrete behind the bar while preventing build-up on the front face of the bar (Fig. 8.4). If sloughing does occur behind the bar because of excess mixing water, voids can develop and contribute to the corrosion in the reinforcing bar. Where bars are closely spaced, more than one bar may be shot from each position.

In gunning walls, application should begin at the bottom (Fig 8.3). The first layer should, if possible, completely encase the reinforcement adjacent to the form.

An important technique for applying a thick [over 6 in. (150 mm)] single layer of shotcrete against a vertical surface is "shelf" or "bench" gunning. Instead of gunning directly against the surface, a thick layer of material is built up, the top surface of which is maintained at approximately a 45 deg slope (Fig. 8.5). In gunning slabs, the nozzle should normally be held at a slight angle from the perpendicular so that the rebound is blown onto the completed portion where it can be removed.



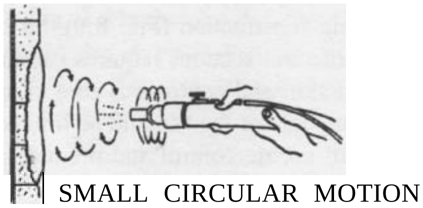


Fig. 8.2-Manipulating the nozzle to produce the best shotcrete

Fig. 8.3-Wet gunning around reinforcing bars. Shotcrete is 11 in. (280 mm) thick

When inside comers 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. 8.6). This will prevent rebound and overspray from filling the comers and being covered up. In the dry-mix method, slight overwetting of the initial layer helps bond and reduces rebound.

It is important to maintain a clean receiving area free of rebound, overspray, and other debris. The use of an air blowpipe is helpful, but preventive or corrective measures by the nozzleman are most effective (Fig. 8.7).

8.5.8 *Multiple layers*-Where 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, and rebound should be removed by brooming, scraping, or other means. Any surface deposits which take a final set should be removed by sandblasting and the surface cleaned with an air-water blast from the nozzle. In addition, the surface should be thoroughly sounded .with a hammer for hollow areas resulting from rebound pockets or lack of bond. Hollows, sags, or other defects should be cut out. Surfaces to be shot should be damp. 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. 8.8).

8.5.9 *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. 8.9). Successful use of shotcrete in structural sections requires careful planning and forming, and 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.

To permit the escape of air and rebound during the gunning operation, columns should be formed only on two adjacent sides wherever practicable; however, satisfactory results may be obtained where three sides are formed provided the width is at least one and one-half times the depth. Pilasters may be formed on two adjacent or opposite sides. The soffit and one side of a beam should be formed; this will provide the maximum area of escape for air and rebound during the shotcrete build-up. Shores should be provided below the soffit in such a manner that no deflection will occur under the load to be imposed.

Where the section contains two curtains of reinforcement it may be desirable to delay the placement of the second curtain until the first curtain has been embedded with shotcrete. However, satisfactory results may be obtained in gunning through two curtains of steel provided the curtain next to the nozzle has a minimum bar spacing of 12 diameters in both directions, and the back curtain has a minimum bar spacing of 6 diameters in both directions.

It is generally not advisable to apply shotcrete in narrow slots or holes. Shotcrete should not be used for constructing spirally reinforced columns or piling.

8.5.10 *Rebound and overspray*-Rebound and overspray are two of the unwanted by-products of shotcreting as shown in Fig. 8.10. Both can be controlled or minimized with the proper nozzle expertise. Overspray is material carried away from the receiving surface and has similar characteristics in both the wet- and dry-mix methods. It adheres to ground wire, shooting strips, forms, reinforcing steel, and other projections, leaving an unconsolidated thickness of low quality shotcrete (Fig. 8.11). It should be removed, preferably before it hardens. If left in place and covered with fresh shotcrete it may cover hollows and sand pockets.

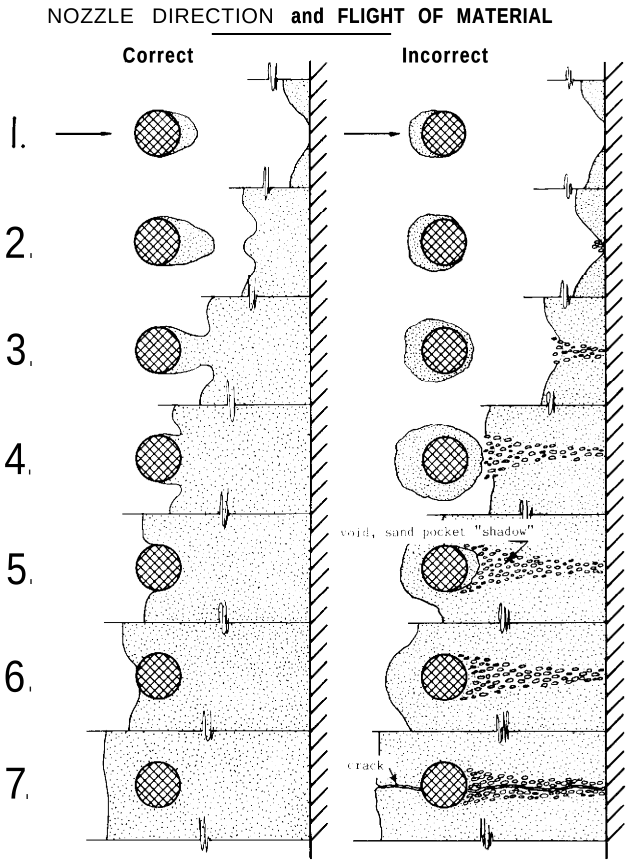


Fig. 8.4-Correct (left) and incorrect (right) method of encasing reinforcing bars with shotcrete

Rebound is aggregate and cement paste which 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, air pressure, cement content, water content, maximum size and gradation of aggregate, amount of reinforcement, and thickness of layer.

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

Rebound should not be worked back into the construction by the nozzleman; if it does not fall clear of the work it must be removed. Rebound should not be salvaged and included in later batches because of the danger of contamination; also, the cement content, state of hydration, and grading of the aggregate are all variable and unpredictable.

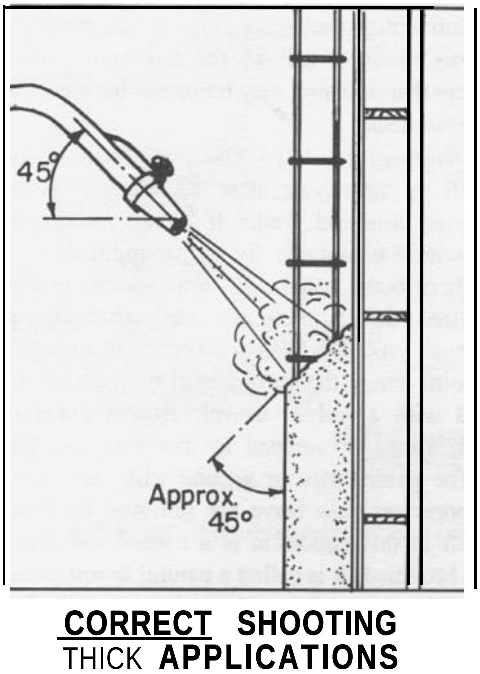


Fig. 8.5-Bench or shelf gunning of shotcrete

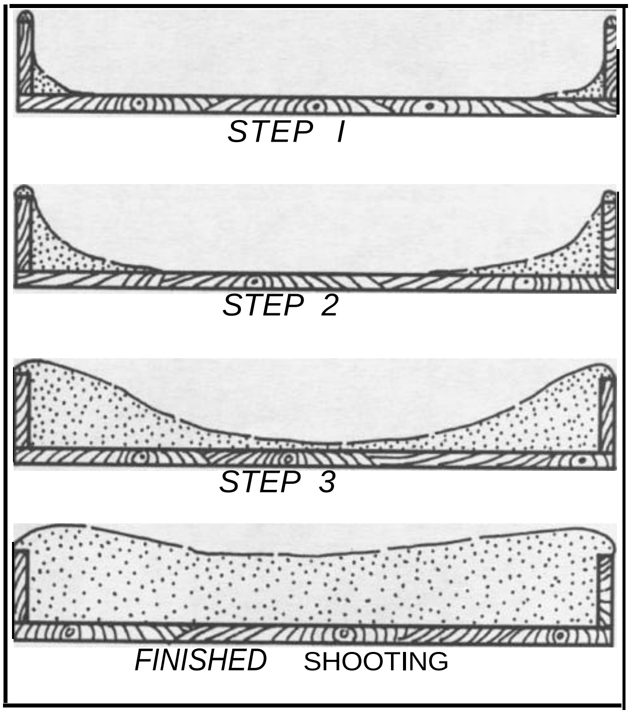


Fig. 8.6-Proper procedure for gunning corners

Fig. 8.7-Blowpipe operator cleaning overspray and rebound in advance of nozzleman

Fig. 8.8-Dry gunning final coat of 1 to 1½ in. (25 to 38 mm) of shotcrete to previously gunned wet shotcrete base (see Fig. 8.3)

Fig. 8.9-Dry-mix shotcrete pilaster between two concrete tilt-up panels (gunning on left, steel trowled finish on pilaster at right)

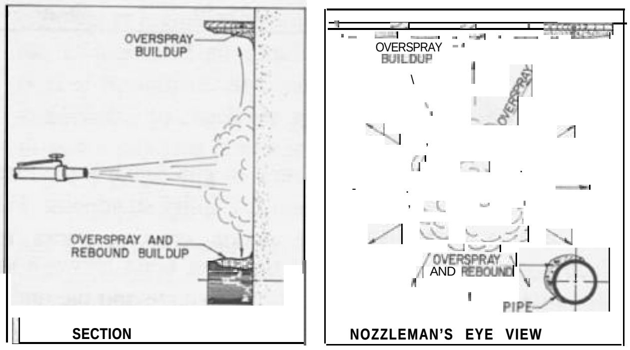


Fig. 8.10-Overspray and rebound

Fig. 8.11-Overspray on reinforcing bars at the top of a band of shotcrete. If the overspray is permitted to harden, and remain on the bars during the next application of shotcrete it will be impossible to fill behind the bars with good shotcrete. Large hollows will remain within the wall, promoting cracking and moisture penetration.

The figures in Table 8.1 show approximate rebound losses for dry- and wet-mix shotcrete. They may be higher or lower depending on the expertise of the individual nozzleman.

8.5.11 *Suspension of work*-Gunning should be suspended under the following inclement weather conditions:

(1) High winds preventing proper application procedures

(2) Temperatures approach freezing and the work cannot be protected

(3) Rain causing washouts or sloughing of the fresh shotcrete

TABLE 8.1-REBOUND LOSSES

Surface	Percent of rebound	
	Dry mix	Wet mix
Floor or slabs	5-15	o-5
Sloping and vertical walls	15-25	5-10
Overhead work	25-50	1 0-20

8.6-Finishing

In dry-mix shotcrete the natural or gun finish is the ideal finish from both a structural and durability standpoint. Further finishing may disturb the section, creating cracks, reducing internal cohesion, and breaking bond between the shotcrete and the reinforcement or shotcrete and the underlying material. Additional finishing may not be easily accomplished because dry-mix shotcrete is usually stiff and difficult to work under normal trowel manipulation. Unlike concrete, shotcrete has little excess water to provide the particle lubrication necessary to promote effective finishing.

Wet-mix shotcrete follows the same procedures as dry-mix except that finishing may be somewhat easier due to the higher consistency.

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 which is suitable for many applications. In those cases where better alignment, appearance, or smoothness are required, the shotcrete is placed a fraction beyond the guide strips, ground wires, or forms. It is allowed to stiffen 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. 8.12). The guide strips or ground wires are then removed and 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 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 is a thin surface coating up to ¼ in. (6 mm) thick containing fine No. 1 gradation sand, passed through a No. 4 sieve eliminating the larger particles that complicate finishing. The mixture is applied fairly wet at nozzle distance of 8 to 12 ft (2.4 to 3.6 m) at low volume and high pressure, giving a finely textured, stucco-like finish. The flash coat is applied to the shotcrete surface which was left about ¼ in. (6 mm) low either immediately after screeding or at a later time and is rodded as described in Section 8.6.1.

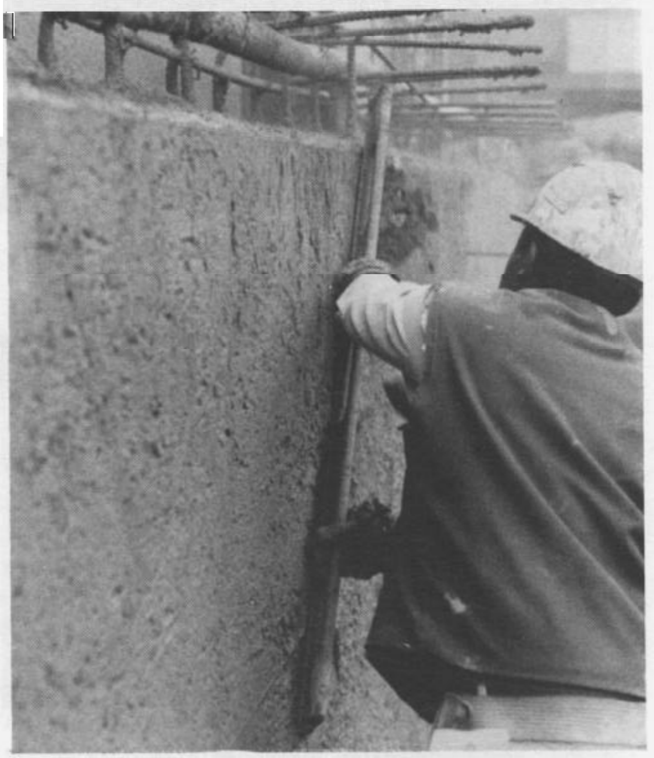


Fig. 8.12-Screeding excess or overgunned shotcrete leaving rough textured finish

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. (6 to 25 mm) of the final grade. A thin surface or finish coat, 1/4 to 1 in. (6 to 25 mm) may be applied immediately after screeding or at a later time. If the finish coat is applied later the base shotcrete must be left properly scarified or broomed. Just prior to the application of the final or finish coat the receiving surface is washed down with an air-water blast. The finish coat may utilize sand similar to that used in the base coat.

8.6.3 *Final finishes*-If desired, the flash or finish coat may be finished in one of the following ways.

8.6.3.1 *Wood float*. This procedure leaves a uniform but granular texture. It is also used as a preliminary finish for other surface treatments.

8.6.3.2 *Rubber float.* A sponge rubber float is applied directly to the flash coat or wood float finish leaving a somewhat finer finish.

8.6.3.3 Brush finish. A fine hairbrush float finish giving a finely textured, sandy finish.

8.6.3.4 *Steel trowel.* A steel trowel finish is applied to a wood float finish leaving a smooth, hard finish. This finish is difficult to achieve requiring considerable effort. It is not recommended. Most shotcrete finishes are more coarsely textured than their concrete counterparts (Figs. 8.13a and 8.13b).

8.7-Curing

Shotcrete, like concrete, must be properly cured so that its potential strength and durability are fully developed. This is particularly true for the thin sections, textured surfaces, and low water-cement ratios associated with shotcrete. The best method for curing is keeping the shotcrete wet continuously for 7 days while maintaining a temperature over 40 F (5 C).

Curing compounds are satisfactory for curing if drying conditions are not severe and where no additional shotcrete or paint is to be applied and the appearance is acceptable. Where the surface has a natural gun or flash finish, the liquid membrane curing compound should be applied heavier than on surfaces with a finer finish. A rate of 100 ft^2/gal (2.4 m^2/L) should be adequate. Natural curing may be allowed if the relative humidity is at or above 85 percent. More detailed information on curing may be found in ACI 308 and ACI 506.2.

Rapid drying of shotcrete at the end of the curing period should be avoided.

8.8-Hot weather shotcreting

The problems associated with mixing and placing shotcrete during hot weather are more acute with wet-mix than with dry-mix shotcrete. With dry-mix shotcrete it is desirable that the time from mixing to gunning a mix does not exceed 15 min; otherwise, undesirable decreases in strength due to prehydration can occur. With wet-mix shotcrete the undesirable effects are similar to ordinary pumped concrete.

The problems include increased water demand, increased rate of slump loss, increased rate of set and difficulty in regulating entrained air content. Procedures must be developed to handle these problems so as to insure a satisfactory shotcrete installation.

Once the shotcrete is in place, both methods follow similar finishing and curing procedures. Screeding and finishing operations should proceed as rapidly as the shotcrete conditions allow. Curing should be started 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 305 should be referred to for more detailed information.

Fig. 8.13a—Applying a steel trowel finish to freshly gunned shotcrete surface

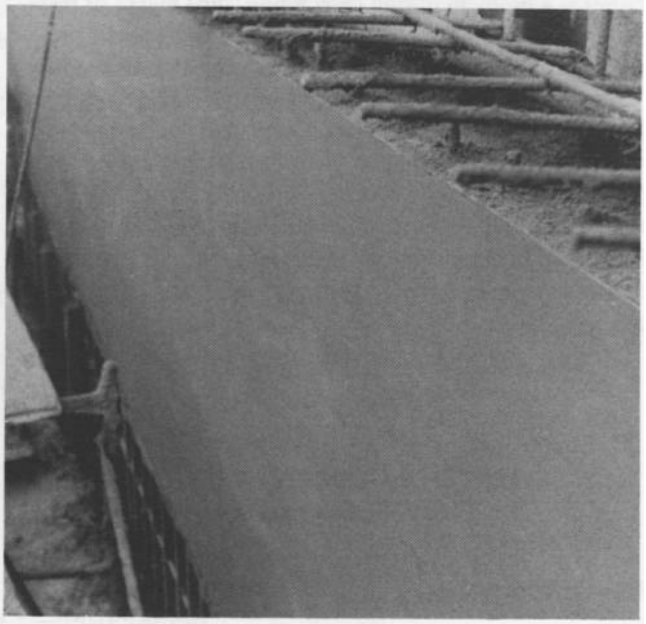


Fig. 8.13b-Final fmish appearance

8.9-Cold weather shotcreting

Shotcrete should not be placed on frozen surfaces. This and other precautions used to protect concrete from freezing should be used for protecting shotcrete. Shotcrete has a greater heat of hydration because of its high cement factor which aids in resisting freezing but it is placed in thin layers with large surface areas, providing for rapid loss of heat which partially counter balances the heat of hydration benefits. If the temperature is not fluctuating too widely, gunning can be allowed if the temperature is at least 40 F (5 C) and rising and discontinued at 40 F (5 C) and falling. Shotcrete that is not subjected to freezing temperatures before it has reached a compressive strength of 500 psi (3.4 MPa) will not be damaged by subsequent freezing. However, at low temperatures, strengths will not develop until higher temperatures are restored.

Once the shotcrete is in place and finished it should be cured, preferably with steam. If steam curing is impractical, a liquid membrane curing compound may be used. Water curing in a freezing environment is not recommended. The temperature during curing should be maintained above 40 F (5 C).

Refer to ACI 306R for more information on all aspects of cold weather shotcreting.

8.10-Precautions

Since rebound can be projected in all directions it is important that all personnel in the vicinity of the nozzle operation wear proper eye protection and that the rebound be prevented from harming the passing public or adjacent property. Some personnel may be affected by cement which can cause dry cracked skin, dermatitis, and burns. Other ingredients such as admixtures and special proprietary mixtures may create additional hazards. Proper protective devices, ointments, and clothing should be used. Special attention should be given and precaution exercised in enclosed areas. Where dust, mist, or other airborne particulate matter is a problem during shotcreting, dust masks or respirators should be employed by personnel, and special provisions for ventilating the work area should also be made.

The use of fibers in the shotcrete can produce problems for personnel during the shotcreting and finishing operations. The nozzleman and any helpers should have complete face and eye protection and clothes that cover all skin areas. Workers should be aware that fibers can collect in clothing. Protruding fibers in the shotcrete surface can pose a hazard to finishers. A flash coat of plain shotcrete can eliminate this problem.

CHAPTER 9-QUALITY CONTROL

9.1-Introduction

Shotcrete is a unique material with many unusual applications that require careful attention to details from design through construction. To a significant degree it is more art than science. It is therefore essential that quality control procedures be established to assure 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, craftmanship, and installation techniques.

The size and character of the application usually determines the amount of effort which 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. The implementation of a quality control program for a shotcrete installation requires an enlightened approach. Whoever is entrusted with this task must have understanding of and experience in the application of shotcrete and have sufficient flexibility to adapt the specifications to field conditions. Reference standards referred to in this chapter may be found in Chapter 10.

ACI 506.2 should be used as the basis for the quality control procedures.

9.2-Design and quality control

Proper design is a most 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 mix proportions. Quality control assures that these items are as designed; it will not assure 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 the most suitable procedure.

Mixture proportions may be detailed in the specification or may be selected by the contractor to produce a specified compressive strength or other properties.

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 of this guide 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, gunning equipment, mixers and batchers, and hoses should be properly maintained, cleaned, calibrated, and checked regularly for proper function.

9.5-Craftsmanship

Criteria for personnel qualification are outlined in Chapter 4. Only craftsmanship of the highest order will produce high quality shotcrete. There are two basic procedures to help assure the desired craftsmanship; applicator evaluation and preconstruction testing. ACI 506.3R provides a procedure for certification of shotcrete nozzlemen. It is recommended that job specifications include the requirement for this certification.

The applicator should have a traceable history of acceptable quality shotcrete work similar to that required for the project at hand. It is preferred that the principals and the shotcrete crew 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 utilizing the personnel, materials and equipment to be used on this project are outlined in ACI 506.2. Tests should be conducted under similar conditions 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. It is essential that the procedures and techniques described in other portions of this guide be followed closely since they represent good shotcrete practice.

9.7—Inspection

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

9.8-Testing procedures

An important aspect of quality control is the physical testing of the shotcrete before, during, and after placement.

ACI 506.2 describes in full the procedures to be followed in preconstruction and construction testing.

Normal testing ages for compressive strength are 7 and 28 days; however, shorter periods may be required under particular applications or conditions.

Some additional tests that may be required of freshly placed shotcrete are water content and cement content. Others include tests for water absorption, drying shrinkage, and resistance to freeze-thaw cycles.

Acceptance of shotcrete should be based on results obtained from drilled cores or sawed cubes. 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.

CHAPTER 10-REFERENCES

10.1-Specified and/or recommended references

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation, including year of adoption or revision. The documents listed were the latest effort at the time this document was written. Since some of these documents are revised frequently, generally in minor detail only, the user of this document should check directly with the sponsoring group if it is desired to refer to the latest revision.

American Concrete Institute

211.1-81 (Revised 1985)	Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
214-77 (Reaffirmed 1983)	Recommended Practice for Evaluation of Strength Test Results of Concrete
301-84 (Revised 1988)	Specifications for Structural Conrete for Buildings
304.2R-71 (Revised 1982)	Placing Concrete by Pumping Methods
305R-77 (Revised 1982)	Hot Weather Concreting
306R-88	Cold Weather Concreting
308-81 (Revised 1986)	Standard Practice for Curing Concrete
318-83 (Revised 1986)	Building Code Requirements for Reinforced Concrete
506.2-77 (Revised 1983)	Specification for Materials, Proportioning, and Application of Shotcrete
506.1R-84	State-of-the-Art Report on Fiber Reinforced Shotcrete
506.3R-82	Guide to Certification of Shotcrete Nozzlemen
547R-79 (Revised 1983) (Reapproved 1987)	Refractory Concrete: State-of-the-Art Report

ASTM

A 185-85	Standard Specification for Welded Steel Wire Fabric for Concrete Reinforcement
A 385-80 (1986)	Standard Recommended Practice for Providing High-Quality Zinc Coatings (Hot Dip)
A 416-86	Standard Specification for Uncoated Seven-Wire Stress-Relieved Steel Strand for Prestressed Concrete
A 421-80 (1985)	Standard Specification for Uncoated Stress-Relieved Steel Wire for Prestressed Concrete
A 497-86	Standard Specification for Welded Deformed Steel Wire Fabric for Concrete Reinforcement

A 615-87a	Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement
A 616-87	Standard Specification for Rail Steel Deformed and Plain Bars for Concrete Reinforcement
A 617-87	Standard Specification for Axle-Steel Deformed and Plain Bars for Concrete Reinforcement
A 641-82	Standard Specification or Zinc-Coated (Galvanized) Carbon Steel Wire
A 706-88	Standard Specification for Low-Alloy Steel Deformed Bars for Concrete Reinforcement
A 722-88	Standard Specification for Uncoated High Strength Steel Bars for Prestressing Concrete
A 767-88	Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement
A 775-88a	Standard Specification for Epoxy Coated Reinforcing Steel Bars
C 33-86	Standard Specification for Concrete Aggregates
C 42-87	Standard Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 94-86b	Standard Specification for Ready-Mixed Concrete
C 109-87	Standard Method of Test for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. (50-mm) Cube Specimens)
C 150-86	Standard Specification for Portland Cement
C 171-69 (1986)	Standard Specification for Sheet Materials for Curing Concrete
C 260-86	Standard Specification for Air-Entraining Admixtures for Concrete
C 309-S 1	Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete
C 330-87	Standard Specification for Lightweight Aggregates for Structural Concrete
C 494-86	Standard Specification for Chemical Admixtures for Concrete
C 595-86	Standard Specification for Blended Hydraulic Cements
C 597-83	Standard Test Method for Pulse Velocity Through Concrete
C 617-87	Standard Method for Capping Cylindrical Concrete Specimens
C 618-87	Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete
C 685-86a	Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing
C 803-82	Standard Test Method for Penetration Resistance of Hardened Concrete
C 805-85	Standard Test Method for Rebound Number of Hardened Concrete
C 900-87	Standard Test Method for Pullout Strength of Hardened Concrete
D 98-87	Standard Specification for Calcium Chloride

Steel Structures Painting Council

SSPC-SP6	Commercial Blast Cleaning, Steel Structures Painting Manual, V.2, 1982

The above publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 19150
Detroit, Mich. 48219

ASTM
1916 Race St.
Philadelphia, Pa. 19103

Steel Structures Painting Council
4400 Fifth Ave.
Pittsburgh, Pa. 15213

10.2-Cited and other references

1. Litvin, Albert, and Shideler, J. J., "Structural Applications of Pumped and Sprayed Concrete," *Development Department Bulletin* No. D72, Portland Cement Association, Skokie, 1964, 29 pp.
2. Shotcreting, SP-14, American Concrete Institute, Detroit, 1966, 224 pp.
3. Lorman, William R., Engineering Properties of Shotcrete, SP-14A, American Concrete Institute, Detroit, 1968, 58 pp.
4. Use of Shotcrete for Underground Structural Support, SP-45, American Concrete Institute/American Society of Civil Engineers, Detroit, 1973, 465 pp.
5. Shotcrete for Ground Support, SP-54, American Concrete Institute/American Society of Civil Engineers, Detroit, 1976, 776 pp.
6. Concrete Manual, 8th Edition, U.S. Bureau of Reclamation, Washington, D.C., 1975, pp. 478-486.
7. "Gunite," Brochure No. G-84,, Gunite Contractors Association, Los Angeles, 1976.
8. Ryan, T. F., Gunite-A Handbook for Engineers, Cement and Concrete Association, Wexham Springs, 1973, 63 pp.
9. Crom, T. R., "Dry Mix Shotcrete Nozzling," The Crom Corp., Gainesville, 1978.
10. "Application and Use of Shotcrete," ACI Compilation No. 6, American Concrete Institute, Detroit, 1981, 92 pp.
11. Refractory Concrete, SP-57, American Concrete Institute, Detroit, 1978, 314 pp.
12. Ward, W. H., and Hills, D. L., "Sprayed Concrete: Tunnel Support Requirements and the Dry Mix Process," Shotcrete for Ground Support, SP-54, American Concrete Institute/American Society of Civil Engineers, Detroit, 1977, pp. 475-532. Also, Current Paper No. 18/77, Building Research Establishment, Garston, Watford, 1977.

APPENDIX A-PAYMENT FOR SHOTCRETE WORK

A.1-Introduction

Many factors must be taken into consideration when establishing the best basis 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. It is essential that all factors (Section A.3) peculiar to a specific project 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, are to be included in the shotcrete pay item. The work items that should be considered are: (a) surface preparation, (b) formwork, (c) anchorage-support and spacers, (d) reinforcement, (e) quality control, and (f) coating (painting) the shotcrete if required. Alignment control, joints, and protection of adjacent surfaces are usually included in the shotcrete item.

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

A.2-Payment bases

Payment for shotcrete work is made on one or more of the bases shown in Table A.1, or a combination thereof, depending on the nature and scope of the project.

TABLE A.1-PAYMENT BASES FOR SHOTCRETE*

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

*See Section A.5 for definition of classes.
†See Section A.5.3.1.
‡See Section A.5.3.2.

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. However, most projects are not that simple in concept or execution and the following factors should be considered in establishing a basis for payment.

A.3.1 *Geometry or work configuration*-The shape of the area to be shotcreted will determine to a great extent the best basis 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 Class B or C method of payment is recommended.

A.3.2 *Job conditions*-Certain projects have working conditions which 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 basis 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 provision 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*-There are many shotcrete applications where 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 most 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 on a Class A basis. 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*-It is important that all the elements which will aid in providing a well executed and satisfactory shotcrete job be written into the specification. Type of process (wet- or dry-mix), materials, design mix, admixtures, quality and method of preparation, anchorage and reinforcing 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 the Class A and C bases 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, it may be advisable to use a Class B method of payment with a conscientious applicator who has been prequalified.

A.4-Supplementary items

In most cases, surface preparation, formwork, anchorage, reinforcement, quality control and coating, are included in the shotcrete pay item. However, there are instances 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: (a) concrete, (b) steel, (c) wood, (d) rock, and (e) earth. Usually these items are compatible with the shotcrete pay item, especially when they are small in quantity. However, where the volume of work is large, 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 and/or spacing 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 fabric, reinforcing bars, or special anchors and usually is included in the shotcrete pay item.

A.4.5 *Quality control*-The costs 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.

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 take into consideration 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 must be made in a manner that will insure 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. This type 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 and/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)*-These methods are used primarily where the scope and extent of the work cannot be determined prior to 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.* Such methods 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 must 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 must 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.* This method utilizes the volume of materials used in the mixture, usually the volume of cement, multiplied by a specified conversion factor which will result in the approximate volume of material in place. Attention must be given to proportioning and rebound waste, since 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 this type of 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.* In this case a specified area and depth are given and payment is based on the completed area in square 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 the following items:

(a) Mobilization and demobilization

(b) Straight and overtime rates for specified types and quantities of labor and equipment

(c) Prices for required materials

Cost of additional labor of each type should be 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 the following items:

(a) Hourly or per diem wages for each classification of labor

(b) Cost of insurance, unemployment taxes, worker's compensation, fringe benefits

(c) Hourly or per diem rates for required equipment

(d) Rates for material including transportation and taxes

(e) Percentages for profit and overhead

Time sheets including labor hours, equipment, and material charges should be 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 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.

This report was submitted to letter ballot of the committee which consists of 22 members; 17 members returned ballots, all of whom voted affirmatively.