Chapter 3
Materials, Proportioning, and Properties

The materials, mixture proportions, and properties of shotcrete are similar in many respects to conventional concrete. Much of the guidance of EM 1110-2-2000 for conventional concrete applies to shotcrete as well.

3-1. Cementitious Materials

a. Portland cement.

(1) Cement requirements for shotcrete are similar to those for conventional concrete. Portland cement must meet the requirements of CRD-C 201[1] (American Society for Testing and Materials (ASTM) C 150), Type I or II. Where the shotcrete will be exposed to soil or water high in soluble sulfates, Type II or V should be used as described in EM 1110-2-2000. Blended cement must meet the requirements of CRD-C 203 (ASTM C 595), Type IP or IS, and moderate sulfate resistance may be specified by adding the suffix MS to the type designation. Where structural requirements require high early strength, Type III meeting the requirements of CRD-C 201 (ASTM C 150) cement should be considered.

(2) Low-alkali cement must be specified when the aggregates used are regarded as chemically reactive with the alkalies in the cement (see EM 1110-2-2000).

(3) Air-entraining cement has been used with the wet-mix process and has achieved varied results, with the air content generally much lower than in conventional concrete. Generally, the use of air-entraining cement is not recommended, since in-place air contents are affected by external factors such as air pressure, hose lengths, and equipment type. AEA's allow flexibility to compensate for these factors.

b. Pozzolan. When added to a portland-cement matrix, pozzolan reacts with the calcium hydroxide and water to produce more calcium silicate gel. Consequently, shotcretes with pozzolan may exhibit improved long-term strength performance and lower permeability. Pozzolan is sometimes added to wet-mix shotcrete to enhance workability, improve pumpability, increase resistance to sulfate attack, and reduce expansion caused by the alkali-silica reaction. The use of fly ash facilitates pumping shotcrete long distances. Portland cement replacement with pozzolan should be carefully considered, since early age strength development is delayed. Pozzolans should conform to CRD-C 255 (ASTM C 618). Natural pozzolans and fly ash are not typically used with dry-mix shotcrete. However, silica fume is often used in dry-mix shotcrete and does not delay strength development.

c. Silica fume.

(1) Silica fume is an extremely fine, amorphous pozzolanic material which is a waste product of the silicon, ferrosilicon, or other silicon alloy production in submerged-arc electric furnaces. The silica fume condenses from the exhaust gases forming extremely minute spherical particles. The material is over 85 percent silica dioxide, is approximately 100 times finer than portland cement, and has a specific gravity ranging from 2.1 to 2.6.

(2) Silica-fume additions create several favorable conditions in shotcrete. Because of the pozzolanic nature of silica fume, its addition results in improved strength and durability. Because of the its extreme fineness, silica fume particles fill the microscopic voids between cement particles further reducing permeability and increasing the density of the shotcrete. Shotcrete mixtures with silica-fume additions display increased adhesion and cohesion.

(3) Since silica fume is so fine, the material cannot be effectively handled in its dry, natural form. Consequently, silica fume is commercially available in several processed forms. In one form, silica fume is densified to 30 to 40 pounds per cubic foot (pcf) loose bulk density. Further modifications include the addition of powdered water-reducing admixtures (WRA) to produce a formulated product. Silica fume is also available in a pelletized form. Significant mixing action is necessary to completely break down and dissolve the pellets. Slurried silica fume is produced by mixing nearly equal weights of silica fume and water. Slurries are also further modified to include water-reducing admixtures.

(4) Silica-fume additions to wet-mix shotcrete must be made in conjunction with the addition of normal and

[1]All CRD-C designations are to *Handbook for Concrete and Cement*, 1949, US Army Engineer Waterways Experiment Station. Parenthetical references are ASTM equivalents.

high-range WRA's. Silica-fume additions without WRA's would necessitate large water additions to maintain a suitable workability level. The additional water increases the water-cement ratio and negates the benefits of the silica-fume addition. On the other hand, WRA's are not recommended for silica-fume additions to dry-mix shotcrete since the total mixture is in contact with water for only the time when the mixture exits the nozzle and impacts the shooting surface. The use of WRA's into dry-mix shotcrete would cause the compacted shotcrete to slough and sag on the surface as the admixture takes effect.

(5) For wet-mix shotcrete, any of the packaging processes are applicable. If the silica fume is not prepackaged with a WRA, such an admixture must be batched. Dry-mix shotcrete is best proportioned using dry processed products of silica fume.

3-2. Aggregate

a. Aggregate should comply with the quality requirements of CRD-C 133 (ASTM C 33). Table 3-1 shows acceptable grading limits. Grading No. 1 should be used if a mortar mixture is desired. Gradings No. 2 and 3 contain coarse aggregate; the latter is similar to a conventional 19.0-mm (3/4-inch) nominal maximum size aggregate, except for a reduction in the larger sizes to minimize rebound. Aggregate failing to comply with these gradings may be used if preconstruction tests demonstrate that it gives good results. However, a uniform grading is essential. Coarse and fine aggregate should be batched separately to avoid segregation.

b. Fine aggregate for finish or flash coats and certain other special applications may be finer than Grading No. 1. Finer fine aggregates, however, generally produce shotcretes having greater drying shrinkage, while coarser sands result in more rebound.

c. Lightweight-aggregate shotcrete is most practical for the dry-mix process. Since moisture and aggregate contact is initiated at the nozzle, the severe workability reductions common in conventional lightweight concrete production do not occur.

3-3. Water

a. Mixing water. Potable water should be used. If this is not available, the proposed water source should be tested according to CRD-C 400.

b. Curing water. No special requirements are necessary for curing water applied to shotcrete (ASTM 1978). Water for curing of architectural shotcrete should be free from elements that will cause staining.

3-4. Chemical Admixtures

a. Use of admixtures. Because of shotcrete equipment limitations, the use of admixtures in shotcrete is not the same as in conventional concrete. Admixtures should be tested in the field prior to use on large jobs to ensure that the desired properties are achieved. Chemical admixtures used in shotcrete should comply with the appropriate requirements given in CRD-C 625 (ASTM C 1141). ACI 212.3R (paragraph A-1, ACI (1991a)), "Chemical Admixtures for Concrete," contains detailed information on general use in concrete.

b. Air-entraining admixture (AEA). The use of AEA's in shotcrete is practical only in wet-mix shotcrete.

Table 3-1
Grading Limits for Aggregate

	Percent by Mass Passing Individual Sieves		
Sieve Size	Grading No. 1	Grading No. 2	Grading No. 3
3/4-inch			100
1/2-inch		100	80-95
3/8-inch	100	90-100	70-90
0.19 inch (No. 4)	95-100	70-85	50-70
0.093 inch (No. 8)	80-100	50-70	35-55
0.046 inch (No. 16)	50-85	35-55	20-40
0.024 inch (No. 30)	25-60	20-35	10-30
0.012 inch (No. 50)	10-30	8-20	5-17
0.006 inch (No. 100)	2-10	2-10	2-10

Due to the loss of air during the gunning process of the wet-mix shotcrete, the AEA should be batched so that the measured air contents in the plastic mix prior to pumping are twice the desired hardened shotcrete air content. The mixing process required to form the air bubbles does not occur in the dry-mix process, hence a suitable air-void system is not generated using the admixture. Air entrainment has slightly reduced rebound.

c. Water-reducing and retarding admixtures. WRA's meeting the requirements of CRD-C 87 (ASTM C 494) are readily adapted to the wet-mix process but are not used in dry-mix shotcrete due to the ineffectiveness of the admixture when adding the admixture and water at the nozzle. Retarding admixtures are seldom used in shotcrete, except for near horizontal surfaces where subsequent finishing of the shotcrete surface is required.

d. Accelerators.

(1) Accelerators are essential in some shotcrete applications, such as tunnel support, where rapid section buildup and rapid strength development are necessary. Early accelerators were powders consisting of soluble aluminates, carbonates, and silicates. Modern accelerators, both powdered and liquid, fall into a wide assortment of chemical makeups. Accelerators have different effects depending on their chemistry, the chemistry of the cement, and the dosage rate of the admixture. Some of the commercial accelerators contain calcium chloride. Many are caustic, particularly the powdered materials, although not as caustic as in the past.

(2) Tests should be made to establish the compatibility of the particular accelerator with the cement proposed for use on the project and to determine the amount of such accelerator required. Many accelerators reduce 28-day strengths by 25 to 40 percent, depending upon the compatibility of the accelerator and cement. Where the aggregate is reactive, the alkali content of the admixture added to that of the cement should not exceed 0.6 percent by mass of the cement.

(3) Accelerators may reduce the frost resistance of the shotcrete. Some may be very caustic and therefore are a safety hazard. For these reasons and because of their cost, accelerators should only be used where necessary and then only in the minimum quantity necessary to achieve the desired results.

(4) Calcium chloride, an accelerator, should never be used in an amount greater than 2 percent by mass of the cement, except where "flash set" is needed for stoppage of leaks. It should not be used in sulfate exposures, nor where the shotcrete encases dissimilar metals (such as aluminum and steel) in contact with each other. No admixtures containing calcium chloride should be used where the shotcrete is in contact with prestressing steel.

(5) Liquid accelerators are generally added at the nozzle for dry-mix or wet-mix shotcrete. Powdered accelerators are generally used only for dry-mix shotcrete, added as a powder to the dry ingredients. Accelerators used in wet-mix shotcrete produce quick stiffening, then initial set. However, the final set usually occurs much later than for dry-mix shotcrete. The time of set can be varied widely with these materials, including initial set in less than 1 minute, and final set in less than 4 minutes. Some of these materials can also be used to create a "flash set" for special applications.

e. Polymers. The addition of certain latex emulsions to a conventional portland-cement shotcrete has increased both tensile and flexural strength, improved bonding, and decreased permeability. One common use of these materials has been in the repair of concrete structures in marine environments and those subject to chemical attack. A latex with favorable properties should be selected and the field personnel must be instructed in its behavior.

f. Bonding compounds. Bonding compounds are generally not recommended in shotcrete work, because the bond between shotcrete and properly prepared substrates is normally excellent. When improperly used, bonding compounds can act as bond breakers. Bonding agents should not be used in shotcrete work without an investigation into their effectiveness in each case.

3-5. Reinforcing Steel

a. Reinforcing bars for shotcrete should meet the same specifications as for conventional concrete. Because of the placement method, the use of bars larger than No. 5 or heavy concentrations of steel are not practical. Large bars make it difficult to achieve adequate build-up of good quality shotcrete behind the bar and heavy concentrations of steel interfere with the placement of shotcrete. In general, bar spacings of 6 to 12 inches are recommended for shotcrete reinforcement.

b. It is often advantageous to specify as welded wire fabric, reinforcement either uncoated, galvanized, or epoxy coated. Flat stock should usually be specified in lieu of rolled fabric. Because of the rolled configuration, rolled welded wire fabric is difficult to place at specified locations. Wire spacing should be as wide as possible to allow shotcrete to be built up behind. Spacing of 6 inches is recommended, however wire spacing as low as 2 inches has been used with 4 inches being more typical.

c. In repair work, a thin shotcrete coating may not require reinforcement. When reinforcement is exposed in the old concrete, but not severely corroded, it may be the only reinforcement necessary. In other cases, additional reinforcement (bars or wire mesh) may be required to replace corroded steel to control temperature cracking, if not to satisfy structural considerations.

3-6. Fiber Reinforcement

a. Steel fiber reinforcement. Steel fibers have been used in shotcrete to increase its ductility, toughness, impact resistance, and reduce crack propagation. The fibers are commercially available in lengths ranging from 1/2 to 3 inches. Typical fiber lengths for shotcrete range from 3/4 to 1-1/2 inches and are used in the amount of 1 to 2 percent by volume of the shotcrete. The fibers have little effect on compressive strength and produce only modest increases in flexural strength. However, they provide continued and, at times, improved load carrying capacity after the member has cracked.

b. Steel fiber source. Steel fibers are manufactured in several ways. Wire fibers are produced from drawn wire that has been subsequently cut or chopped. Flat steel fibers are cut or slit from sheet of steel or by flattening wire. The melt-extraction process is used to "cast" fibers by extracting fibers from a pool of molten steel. Consequently, fibers are round, flat, or irregular in shape. Additional anchorage is provided by deformations along the fiber length or at the ends. Deformations can be natural irregularities, crimps, corrugations, hooks, bulbs, and others. Collated fibers and fibers with noncircular cross sections reduce the handling and batching problems common with straight, round fibers.

c. Polypropylene-fiber reinforcement. Collated fibrillated-polypropylene (CFP) fibers are used in shotcrete. Fiber lengths of 1/2 to 2-1/2 inches have been the most common in use. The common application has been 1 to 2 pounds of polypropylene fibers per cubic yard of shotcrete. The primary benefit is to control thermal and drying shrinkage cracking. More recently, polypropylene doses of up to 10 pounds per cubic yard have been used successfully yielding shotcrete toughness performance approaching that of some steel fiber shotcrete (Morgan et al. 1989). The hazard from rebound is much less when polypropylene is used. The most common specified length for polypropylene is 1-1/2 inches, although longer lengths are no problem.

d. Glass fiber source. Glass fibers are made from high zirconia alkali-resistant glass designated AR glass. Glass fibers, used for fiberglass reinforcement, are designated E glass and should not be used in a portland-cement matrix. While glass fibers may be as small as 0.0002 inch, they are usually bonded together into elements having a diameter of 0.0005 to 0.05 inch. Glass fiber lengths are typically 1 to 2 inches, but a wide range of lengths is possible.

e. Applicable technology. ACI 506.1R, "State-of-the-Art Report on Fiber Reinforced Shotcrete" (ACI 1991e), is a comprehensive document covering the full range of fiber shotcrete technology.

3-7. Proportioning of Shotcrete

a. Considerations. In general, conventional concrete technology may be applied to shotcrete proportioning. Prior to mixture proportioning, the following should be considered:

(1) Type of dry-mix or wet-mix shotcrete appropriate for the work.

(2) The specific job constraints on the shotcrete work.

(3) The type of specification.

(a) Performance versus prescription.

(b) Contractor versus Government mixture proportioning.

A mixture proportioning sample submitted is presented in Appendix D.

b. Mixture proportioning trial batching.

(1) Since shotcrete performance is highly dependent on application procedures, trial batching and testing is a critical operation in verifying mixture performance. The batching and mixing of wet-mix shotcrete is practically identical to conventional concrete; only the fabrication of specimens is different. However, dry-mix is a distinct process. It is normal procedure to obtain trial mixture proportions for shotcrete from the contractor. Along with

the proportions, test panels and cores of the shotcrete are highly recommended, as discussed in Chapter 5.

(2) Test panels are particularly important for dry-mix shotcrete because laboratory mixtures cannot duplicate as-shot dry-mix shotcrete. Typically, a performance specification of 12-hour, 7-day and/or 28-day compressive strengths will be specified, along with a grading for the aggregate. Both the wet- and dry-mix methods will yield a higher as-shot cement content and lower coarse aggregate content, due to rebound of the aggregate.

c. Chlorides. The total chloride ion (Cl^-) from all sources including mixing water, cement, admixture, and aggregate should not exceed 0.06 percent by mass of cement for prestressed members. For other reinforced shotcrete applications, this limit is increased to 0.10 percent in a moist environment exposed to chloride and 0.15 percent in a moist environment not exposed to chloride.

d. Nominal maximum size aggregate (NMSA). The selection of NMSA depends on several factors. The major factors are the allowable shrinkage performance, size of the placement, and the rigidity of the substrate. The amount of rebound, inherent in the shotcrete process, depends on the ability of the substrate and the placed shotcrete to cushion subsequently placed shotcrete. Shotcrete for thin linings on rock or concrete experiences high rebound. Thicker sections and sections on soil structures experience lower rebound. For placements of thin layers on hard surfaces, coarse aggregate should be minimized or eliminated in the mixture to minimize rebound.

e. Wet-mix proportioning. Mixture proportioning procedures for the formulation of conventional concrete for pumping applications are applicable for wet-mix shotcrete. The nominal maximum aggregate size is usually 3/4 inch or smaller. The batched cement content will typically range from 500 to 700 pounds per cubic yard. Rich mixtures are common for shotcrete, especially if vertical or overhead shotcrete placement is required. The limiting factor for cement content in a mixture is often governed by the amount of cement necessary for the shotcrete to adhere to a wall or ceiling, not the specified compressive strength. It is not unusual for shotcrete used in vertical and overhead placement to have 28-day strengths in excess of 4,500 psi, due only to the amount of cement necessary to make the shotcrete adhere.

(1) Workability. The slump for wet-mix shotcrete should be near the minimum that the pump will handle. A 3-inch slump should normally be considered the maximum slump to be used. Excess slump will yield lower-strength shotcrete which will tend to slough off of vertical and overhead surfaces.

(2) Entrained air. If air entrainment is to be used, an air content ranging from 8 to 12 percent prior to pumping is typical. The in-place shotcrete will have about one-half of the entrained air that was recorded at the pump.

(3) Admixtures. Additional admixtures generally behave the same in wet-mix shotcrete as they do in conventional concrete. Any admixture should be tested in the mixture proportioning studies and on the test panels prior to usage.

f. Dry-mix proportioning. There is no established method of proportioning dry-mix shotcrete. Since it is not practical to perform laboratory trial mixtures for dry-mix shotcrete, field testing of dry-mix proportions is highly advisable, especially if no field data exist for a given dry-mix. The in-place aggregate grading will be finer than the batched grading due to rebound, especially if larger aggregate sizes are used. As with wet-mix shotcrete, the in-place cement factor will be higher also.

(1) Compressive strength. ACI 506 (paragraph A-1, ACI (1991d)), reports typical data on strength versus cement content of dry-mix shotcrete as shown in Table 3-2.

Table 3-2
Strength Versus Cement Content, Dry-Mix Shotcrete, Typical Data

28-day Compressive Strength psi	Cement Content lb
3,000	500-650
4,000	550-700
5,000	650-850

(2) Workability. The workability of the shotcrete is controlled by the nozzleman at the placement. Water adjustments may be made instantaneously at the placement by adjustment of the water valve.

(3) Entrained air. Air-entraining admixtures have little effect on dry-mix shotcrete since there is no mixing of admixture water and aggregate until impact on the

shooting surface. Some contractors prefer to add an air-entraining admixture to a mix to improve workability.

(4) Admixtures. Accelerators are typically the only admixtures that are used in dry-mix shotcrete. These should be tested to determine that they are compatible with the cement being used and produce the required accelerated times of setting.

(5) Cement content. Cement contents are similar to those used in wet-mix shotcrete. Batch weights for cement of 500 to 700 pounds per cubic yard are typical, with 28-day compressive strengths of more than 4,500 psi common for the mixtures used for vertical and overhead placement.

(6) Water-cement ratio. The batched water-cement ratio for coarse aggregate dry-mix shotcrete typically varies between 0.30 to 0.40.

g. Fiber-shotcrete proportioning.

(1) Steel fiber lengths for shotcrete are typically 1 inch but often range from 3/4 inch to 1-1/2 inches. The fiber should be at least 1/4 inch longer than the diameter of the maximum aggregate size. Shorter fibers are more easily pumped through the system, although more are required for equivalent performance. Fiber batch quantities are dependent on required shotcrete properties. Typical fiber proportions range from 0.5 to 2.0 percent by volume of shotcrete. Deformed fibers and fibers with end anchorage provisions produce shotcrete with properties equivalent to straight fibers at much lower fiber loadings. Since fibers tend to rebound at a greater rate than does aggregate, the fiber batch quantity should be adjusted accordingly.

(2) Proportioning mixtures using glass fibers is discussed by the PCI (1981). Proportioning mixtures using polypropylene fibers is discussed by Morgan et al. (1989).

h. Silica-fume shotcrete proportioning. Silica fume is added to a shotcrete mixture as a cement replacement or in addition to cement. Batch quantities range from 7 to 15 percent by mass of cement. Strength enhancement and decreased permeability is apparent at the lower dosages. Reductions in rebound and increases in cohesiveness for thick applications do not occur until silica-fume dosages exceed approximately 14 percent. Further mixture adjustments to wet-mix shotcrete may be necessary to attain the required workability level.

i. Polymer-modified shotcrete. Polymer emulsions are typically 50 percent solids and 50 percent water. The liquid portion of the emulsion replaces the equivalent volume of water, and the solid portion replaces the same volume of combined solids. Additional adjustments to attain desired workability levels may be required.

3-8. Properties of Shotcrete

As is the case with conventional concrete, shotcrete properties vary dramatically depending on water-cement ratio, aggregate quality, size, and type, admixtures used, type of cement used, and construction practices. The proper use of admixtures, fibers, silica fume, and polymers can improve certain properties. Depending on the needs of the particular application, properties of the shotcrete materials and mixtures should be tested prior to final application.

a. Strength. In terms of compressive and flexural strength, shotcrete can produce strength generally equivalent to conventional concrete. Compressive strengths of up to 12,000 psi have been reported from drilled cores from test panels, and 10,000 psi is often quoted in the literature as a typical high strength. The practicality of strengths over 5,000 psi should be established by laboratory or field testing prior to final use. The ratio between compressive and flexural strength appears to be the same as for conventional concrete. Relationships between water-cement ratio and strength also appear to follow normal patterns, with higher strength associated with lower water-cement ratios. Early strength of shotcrete can be very high, reaching 1,000 psi in 5 hours and 3,000 psi in 24 hours.

b. Bond strength. Although few data on bond strength appear to exist, bond strength with other materials is reported to be generally higher than can be achieved with conventional concrete. ACI 506R (paragraph A-1, ACI (1991d)) and Mahar, Parker, and Wuellner (1975) provide some data on bond strengths of shotcrete to various substrates.

c. Shrinkage. Drying shrinkage is most influenced by the water content of the mixture. Typical values of unrestrained shrinkage range from 600 to 1,000 millionths. Shrinkage is reduced in coarse-aggregate shotcrete and increased in shotcrete without coarse aggregate or shotcrete subject to high rebound. Shotcrete containing silica fume has a tendency to exhibit more shrinkage before setting than shotcrete without silica fume. Procedures similar to those outlined by

Holland (1987) to prevent plastic shrinkage cracking should be implemented.

d. Resistance to freezing and thawing. Wet-mix shotcrete frost resistance is ensured by entraining a proper air-void system. Typically, an air content of 8 to 12 percent in the mixture results in in-place shotcrete having a proper air-void system. Although many dry-mix applications have performed well when subjected to mild freezing and thawing, dry-mix shotcrete is more subject to problems from freezing and thawing than wet-mix shotcrete. This is due to the difficulty in entraining air and creating an adequate air-void system in dry-mix shotcrete.

e. Density and permeability of shotcrete can be excellent, provided good practices are followed in the field.

f. Toughness. The addition of fibers to shotcrete can result in a product displaying significant load carrying capability after the occurrence of the first crack. The relationship of post-crack load capacity to load capacity at first crack is defined as toughness. The type, size, shape, and amount of fiber determines the extent of this performance. The use of the toughness index by load-deflection testing, CRD-C 65 (ASTM C 1018), provides a rational means of specifying and comparing performance. However, recent concerns have developed over the specifics of applying this testing procedure (Gopalaratnam et al. 1991). The reader is advised to consider the cited references and contact CECW-EG for further guidance.