

IN-LB

Inch-Pound Units

SI

International System of Units

Specifying Underground Shotcrete—Guide

Reported by ACI Committee 506

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Specifying Underground Shotcrete—Guide

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Specifying Underground Shotcrete—Guide

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This document provides a guide for owners, contractors, designers, and testing, specifying, and inspection organizations engaged in the application of shotcrete for underground support. The guide provides general information for the selection of constituent materials, and methods to proportion shotcrete. Typical methods of batching, mixing, and handling of proportioned shotcrete materials are detailed along with shotcrete placement methods and equipment.

Keywords: acceptance criteria; batching; inspection; methods of payment; mine(s); mixing; mixture proportioning; placement; quality assurance; quality control; safety; shotcrete; testing; tunneling.

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CHAPTER 1—INTRODUCTION AND SCOPE**1.1—Introduction**

In North America, the term “shotcrete” is used and defined by the American Concrete Institute’s “ACI Concrete Terminology” as “concrete placed by a high-velocity pneumatic projection from a nozzle”, while in Europe, shotcrete is commonly referred to as “sprayed concrete”.

Shotcrete is ideally suited for underground applications in tunneling and mining as an initial support measure in soft ground as well as hard rock, as an installation method for final linings, or in underground rehabilitation or expansion projects.

The pneumatic projection of shotcrete onto a surface at high velocity provides specific quality enhancements that interact with the ground surface and prepared substrates, providing superior bond characteristics, increased density, strength, durability, and toughness. In addition, shotcrete provides the geometric and operational flexibility required for many underground operations and—especially if sprayed using robotic equipment—provides a safer working environment, compared to other support installation methods under unsupported ground or if immediate support is needed. These qualities are desirable in ground support and lining applications and provide economic and technical advantages compared to the other initial support systems and materials.

Cast-in-place (CIP) concrete is widely used in underground tunneling for final linings, especially if a constant cross section geometry over long distances allows the use of highly mechanized formwork. However, if the geometry is changing or the tunnel is too short to justify the investment for a mechanized formwork, shotcrete has many advantages over CIP concrete for final linings due to the inherent flexibility of the method to cover a large range of opening

shapes and sizes. This allows for certain structures such as enlarged cross sections, intersections, or penetrations to be constructed with less effort in comparison to CIP concrete.

Geometrical flexibility for final linings is also a key advantage for rehabilitation and expansion projects. In addition, many of these projects are constructed under stringent operational limitations, providing, for example, very limited and strict time windows for construction. The operational flexibility of shotcrete allows for a stop-and-go installation of concrete and provides a key advantage of shotcrete to other installation methods.

Shotcrete technology has been broadly developed throughout the construction industry over the last century. The evolution of mining and civil tunneling methods has placed unique demands on the materials, equipment, and personnel that comprise current concepts of a shotcrete system for underground support and lining construction. With this gradual evolution in technology and trial and error came acceptance, adaptation, and new means and methods of successful shotcrete application.

The design, working conditions, and placement of shotcrete underground are unique, very demanding, and generally much more challenging than shotcreting above ground. The majority of underground shotcrete is installed overhead or sub-vertical, making the correct installation technique and strength development over time crucial.

The primary focus during shotcrete installation underground is worker safety, due to the need to provide immediate and effective ground support and to use proper installation procedures to avoid fallouts of fresh concrete. For the construction industry as a whole, the specification of a 28-day compressive strength is typically sufficient; however, the early strength performance of underground shotcrete during the first hours or days is often critical. Much of the shotcrete is applied overhead to irregular surface substrate profiles immediately following blasting or other modes of excavation. Geological and groundwater conditions are not always predictable; opening stability and rockfalls present a clear hazard to the underground workers. Conditions may be such that the window available for shotcrete application is minutes or a few hours. The use of accelerating admixtures is a unique feature of underground shotcrete application in that it provides a means of controlled and rapid strength gain immediately following application.

Tunneling or mining activities typically take place on a continuous and cyclical basis. The process of excavation, muck removal or mineral extraction, and ground support installation are repeated in every excavation and support round. To be viable and acceptable, shotcrete application should be an integral part of the overall cycle. This requires that the shotcrete system be reliable, efficient, and effective.

The underground environment can impose significant constraints and demands on the batching, mixing, handling, and placement of shotcrete. The unique logistical demands associated with underground shotcrete application may require access to the underground work area via shaft, adit, and ramp, and the subsequent use of long haulage routes or dropping concrete through a borehole or

slickline. This frequently results in extended handling and discharge times and may require the use of hydration-stabilizing admixtures and always requires a vigilant shotcrete crew to avoid plugs in slicklines and shotcrete equipment. At any time, production can be disrupted, and shotcrete installation delayed or disrupted. This is particularly problematic if ground conditions deteriorate and the demand for

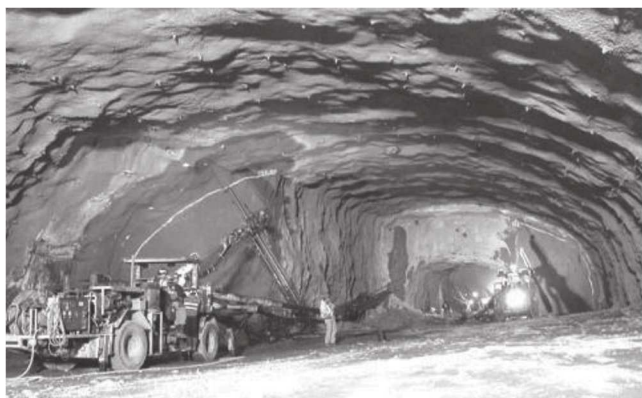


Fig. 1.1a—Typical heading: large tunnel with drill rig.



Fig. 1.1b—Typical heading: small tunnel with drill jumbo.



Fig. 1.1c—Typical heading: mine.

shotcrete as ground support becomes more critical. Finally, the environment can be hostile for worker safety, efficiency, and quality control, as well as for quality shotcrete placement and curing conditions. Figures 1.1a to 1.1c illustrate typical conditions at the heading of tunnels and mines.

These types of challenges have led to specifically designed systems for batching and handling of shotcrete materials, admixtures, placement equipment, installation procedures, and training for underground shotcrete crews. These systems require significant investment not only in terms of capital, but also in providing experienced personnel. Further, the process is complemented by a holistic view on the part of the designer and specifier. Training and supervision have led to improvements in the quality and consistency of shotcrete in underground shotcrete applications. The consequences of deficient shotcrete in any ground support application are obvious and can be unsafe for workers. Quality assurance, quality control, and the associated inspection and testing activities are equally important in achieving a successful underground shotcrete program.

A major task faced by the underground shotcrete industry is the ability to demonstrate to owner, designer, specifier, and inspection and testing personnel that high-quality shotcrete can be produced consistently. It is therefore important that owners and others have an understanding and appreciation of how a shotcrete system—materials, batching, handling, placing equipment, and trained quality supervisory and production personnel—fits into their underground project to ensure that specification requirements are met. The efforts that go into designing, specifying, planning, and implementing a shotcrete program need to be commensurate with the size and complexity of the project. Many small projects require a basic, common-sense approach to quality for which a preconstruction testing and mockup program, which is typical for large and complex projects, may not be necessary. However, there are also small projects that involve a limited volume of shotcrete (for example, repair or rehabilitation) that are both complex and difficult, and where the quality requirements are clearly different. There are also many large underground projects throughout the world where a significant effort is required to staff and conduct extensive quality assurance programs, of which shotcrete is an important part. It is important that owners not be burdened with the cost of unnecessary inspection and testing requirements. For that reason, this guide carefully distinguishes the requirements associated with large, medium, small, and complex shotcrete projects to assist with identifying the optimal approach for the contemplated project.

1.2—Scope

Successful application of underground shotcrete requires teamwork and cooperation of all participants involved in the project. This guide is intended to provide a common basis, information, and background on the application of underground shotcrete for interested owners, designers, specifiers, and inspection and testing personnel.

The guide briefly discusses the concept of composite ground support—the combination of shotcrete and other

Table 1.2—Metrication table

SI to inch-pound	Inch-pound to SI
1 mm = 0.0394 in.	1 in. = 25.4 mm
1 m = 39.37 in. = 3.28 ft	1/3 yd = 1 ft = 12 in. = 0.3048 m
1 m ³ /min = 35.315 ft ³ /min	1 CFM = 1 ft ³ /min = 0.0283 m ³ /min
1 m/s = 3.28 ft/s	1 ft/s = 0.3048 m/s
1 MPa = 145.04 psi	1 ksi = 1000 psi = 6.0 MPa
°C = (°F – 32)/1.8	°F = (1.8 × °C) + 32

support elements used to provide early and effective tunnel support. The guide is not a comprehensive treatise on the design of these systems but is intended to provide sufficient background to understand how the combination and sequencing of ground support elements can influence the performance, application, inspection, and testing of shotcrete.

The general format of the document is such that each section provides a brief introductory overview followed by a table that contains points considered important to specifications (example specifications) and brief notes to the specifier, where necessary. The reader should, however, recognize that each underground project is unique, and that the example specifications and notes to the specifier provided need to be considered in that context.

Although this guide is written to those users typically involved with civil projects involving shotcrete, it is equally applicable to users involved with shotcrete in the underground mining industry. Whereas terms such as owner, specifier, and contractor are ubiquitous for civil projects, these key players are nonetheless involved in mining, except that they are typically one or more individuals, groups, or entities within the mining company, and may be referred to as engineering, production, or quality control.

Measurements in this document are presented in inch-pound units (followed by SI units in parentheses). Table 1.2 contains the constants that were used to convert inch-pound units to SI and vice versa. Due to issues of rounding, significant figures, and the dimensions of locally available products, the values resulting from conversion may be misleadingly precise.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

Not used.

2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

adit—a horizontal or near-horizontal passage leading into a mine or tunnel for the purposes of access, drainage, or ventilation.

air lance—refer to **blowpipe**.

asperity—an irregular surface projection of rock, soil, or substrate causing the surface or profile of a tunnel or excavation to appear rough.

blocking (of steel sets or lattice girders)—wood or steel used to fill in and brace between a steel set or lattice girder and the excavated tunnel profile.

blowpipe—air jet used in shotcrete gunning to remove rebound or other loose material from the work area.

boot—a device placed at the bottom of a vertical slickline to decrease velocity, dissipate energy, and receive wet-mix shotcrete.

delivery equipment—equipment that introduces shotcrete material into the delivery hose.

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

kettle—see **boot**.

MSHA—Manufacturers' Health & Safety Association

nozzle body—a device at the end of the delivery hose that has a regulating valve and contains a manifold (water or air ring) to introduce water or air to shotcrete mixture. A nozzle tip is attached to the exit end of the nozzle body.

pneumatic feed—shotcrete delivery equipment in which material is conveyed by a pressurized air stream.

positive displacement—wet-mix shotcrete delivery equipment in which a pump or other nonpneumatic means pushes the material through the delivery hose in a solid mass.

predampening—the controlled addition of water to shotcrete aggregates or premixed shotcrete materials during batching to adjust the moisture content of the shotcrete mixture to a specified range, usually 3 to 6% by mass, to facilitate consistent, uniform mixing and dust suppression during dry-mix shotcrete application.

quality assurance plan—written project requirements for quality assurance.

quality assurance program—a document that describes the policies, practices, and procedures that will be followed to comply with the quality assurance plan.

quality assurance system—the administrative procedures followed during implementation of the quality assurance plan.

raveling ground—ground characterized by material that tends to deteriorate with time through a process of individual particles or blocks of ground falling from the excavation surface.

rock bolt—a tensioned rock reinforcement element installed in a percussion-drilled hole fully encapsulated with resin or cement grout.

rock dowels—an untensioned rock reinforcement element installed in a percussion-drilled hole fully encapsulated with resin or cement grout

rodman—a worker on a shotcrete crew who trims and finishes shotcrete using a rod or other tools.

slickline—a pipe to carry wet-mix shotcrete to the area of placement.

spider bar—(1) a bent reinforcing bar that attaches a rock bolt plate to a shotcrete shell; or (2) the bent bar used to separate the circumferential bars in a lattice girder.

steel set—structural steel used to support the ground opening in underground construction.

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

CHAPTER 3—SUBMITTALS

3.1—Submittal process

The submittal process is an extremely important aspect of the contracting practice. Complete and comprehensive submittals are essential when it comes to demonstrating the contractor's understanding, commitment, and capability to meet or exceed project quality assurance (QA) and quality control (QC) as well as contractual requirements. Typi-

cally, submittals are required to confirm that specific shotcrete materials, equipment, methods, processes, practice, and personnel have the potential to meet or exceed specified project requirements. The nature and type of submittals should be commensurate with the size and complexity of the underground project.

Submittals are typically required before construction, immediately following the completion of preconstruction testing, and may be required throughout the construction phase of the project. These submittals serve as objective evidence and confirm that specific construction materials, installation methods, equipment, procedures, and trained or qualified personnel have met or exceeded the performance requirements identified in the project specifications and

Table 3.2—Example guide specification for submittals

Section/ Part/ Article	Recommended specification language	Notes to the Specifier
3.1	Preconstruction submittals.	Submittals are usually required from construction contractors at least 28 days before the start of construction. This allows the appropriate project organizations time to review and accept the submittal.
3.1.1	The shotcrete work shall be performed by a Contractor with a minimum of xx years of experience in performing shotcrete work for underground projects with similar size and complexity. Submit objective evidence that documents the qualifications and experience of the contractor and the work crew with projects with similar size and complexity, including the supervisor, shotcrete nozzlemen, and shotcrete equipment operator(s). The shotcrete nozzleman shall be ACI certified for the method (wet or dry) and orientation (vertical or overhead or both) used.	The required years of experience should be defined by the designer and are typically in a range of 5 to 10 years. Personnel qualifications and training results will be required at least 28 days before construction. Shotcrete Nozzlemen Certification by the American Concrete Institute as outlined in ACI CP-60. Larger and more complex projects may in addition specify minimum years of experience with projects of similar size and complexity for the nozzlemen.
3.1.2	Submit manufacturer's certification showing source and proof of conformance to project specifications of all shotcrete materials, including: (a) Portland cement (b) Silica fume (c) Fly ash and slag cement (d) Aggregate source, gradation, bulk density (specific gravity), and absorption (e) Water source (f) Chemical admixtures with materials safety data sheets (MSDS) (g) Fiber reinforcement	Preconstruction testing results will be required at least 28 days before construction. Consider these additional submittals: (a) The hot and cold weather precautions necessary to meet project specifications under these circumstances (b) The chemical composition of all additives and admixtures used in shotcrete, specifically materials safety data sheets (MSDS). For shotcrete materials, refer to ASTM C1436. For water, refer to ASTM C1602/C1602M and C1603.
3.1.3	Submit test records and proof of conformance to project specifications of all ground support reinforcement, including: (a) Rock bolts, rock dowels, and grout (b) Anchor plates and spiders (c) Anchor hardware (nuts and washers) (d) Reinforcing steel or welded wire reinforcement (e) Steel ribs or lattice girders	It is recommended that a shotcrete and ground support equipment submittal identifying the type and performance characteristics of the equipment for ground support installation. This information may be provided elsewhere in the project specifications.
3.1.4	Submit proposed source of shotcrete and shotcrete mixture proportions, including test data from previous experience with mixture proportions, if available. If past data are not available, then trial batching should be required.	Refer to ASTM C1436 for shotcrete materials.
3.1.5	Submit proposed shotcrete mixture proportions, including: (a) Batch quantities of fine aggregate, coarse aggregate, cementitious materials, fibers, expected water demand (to include all water from moisture in aggregates, water added at batch plant, and water added on site), chemical admixtures including accelerators and all other shotcrete ingredients, in lb/yd³ (kg/m³) or fl oz/yd³ (L/m³) based on saturated surface-dry (SSD) aggregates (b) Fiber content of steel fiber or other fibers, in lb/yd³ (kg/m³)	Submittals of proposed shotcrete mixture proportions, supported by 8-hour, 1-day, 7-day, or 28-day compressive and flexural test results within last 24 months as required. Component material submittals will also be required; refer to recommended specification Section 3.2.1.

Table 3.2, cont.—Example guide specification for submittals

3.1.6	Submit proposed methods for mixing, conveying, finishing, curing, and testing along with a complete list of proposed equipment for each task. Submit proposed methods for accelerator dosage control and documentation, including calibration of accelerator pump, if liquid accelerator is used.	Recommend these additional submittals: (a) The shotcrete placement plan (b) Specific provisions to cure and protect in-place shotcrete
3.1.7	Alternative means and methods permitted in the contract documents should be submitted by the contractor for review and acceptance by the owner.	Examples include alternate shotcrete placing equipment and means of groundwater control.
3.1.8	Submit details of proposed safety plan: (a) A description of personal protective equipment, specifically, protective clothing; head, eye, respiratory, and hearing protection; and other safety-related protective devices to be used (b) Copies of MSHA form for all employees on project showing their training is up to date, or submit any related OSHA training forms (c) Description of procedures for handling all potentially hazardous materials, including admixtures, accelerators, and cementitious materials (d) Ventilation plan to ensure proper air quality and enhance visibility for nozzleman and crew (e) Plan for monitoring and controlling respirable dust and vapor (f) Re-entry criteria and related testing if overhead shotcrete is placed	Refer to Chapter 15.
3.1.9	Submit QA/QC program for review and acceptance.	Refer to Chapter 9.
3.2	Submittals during construction.	Depending on the complexity of the project, additional submittals may be as specified. When ground support systems, accessories, and component materials are delivered to the project, materials and manufacturer certifications are required as objective evidence during receipt inspection/acceptance of these materials. These submittals confirm that the quality aspects of items received are in compliance with those obtained under the project procurement process.
3.2.1	Submit results of QC activities.	QC results should be submitted daily or weekly, depending on the complexity of the job.

drawings. Qualified suppliers or vendors usually provide submittals that are subject to evaluation before acceptance by architect/engineer. Where required, preconstruction testing, mockups, and laboratory test results can support these submittals. Such testing may involve prequalification of procedures, materials, equipment, and personnel and applies to shotcrete, but also to concrete, rock bolts, the manufacture of lattice girders and steel sets, or other materials used in underground construction. All quality-affecting services, materials, and equipment are subject to ongoing procurement procedures and controls.

Finally, it should be noted that some submittals are intended for the engineer's review and acceptance prior to or during construction, other submittals are for the construction manager's information to assist with the inspection program, and some submittals provide objective evidence in the project's quality assurance and quality control programs.

The project team should acknowledge the mutual benefits of the submittal process for the project to establish a common ground and understanding and to make the construction process in the field as efficient as possible.

3.2—Recommended specifications

Recommended specifications for submittals are provided in Table 3.2. The information is provided in a guide specification format: the left column provides the recommended specification language; and the right column provides notes to the specifier.

CHAPTER 4—MATERIALS

4.1—Accelerators

Accelerating admixtures (accelerators) are typically used in both dry-mix and wet-mix shotcrete to shorten the time of setting and strength gain. High early strength is often desired in underground construction because it:

- (a) provides immediate and effective ground support in unstable or potentially unstable tunnel conditions or if the excavation is advancing quickly
- (b) reduces convergence of the tunnel and potential surface settlements
- (c) ensures a safe working environment under freshly installed shotcrete, especially overhead
- (d) enhances the maximum buildup thickness and, hence, minimizes shotcrete fallouts, which are not only costly but also present a hazard to the underground working crew
- (e) improves application of shotcrete in ground conditions with dripping or flowing groundwater.

Accelerators vary widely in their chemical composition. The accelerator supplier should be consulted to determine the best type and dosage for the specific application(s), as well as identify potential interaction with other admixtures and additives.

Most accelerators result in lower 28-day strength when compared with a non-accelerated shotcrete mixture (Zhang 2012). In addition, accelerators often create greater paste porosity and, therefore, may reduce shotcrete durability.

with respect to chloride resistance, permeability, appearance of leaching stains, sulfate attack, and freezing-and-thawing action. For these reasons, accelerators should be appropriately prescribed and used.

In general, the accelerator dosage should be kept as low as possible to achieve the targeted performance. In any case, over-acceleration, or so-called “burning out”, of the shotcrete must be avoided. During the pre-construction testing the over-acceleration limit should be evaluated. Clear guidance must be given to the shotcrete crew with regard to the targeted and maximum accelerator dosage.

For mining applications, long-term durability may not be a major concern, depending on the use, location, and projected life of the specific underground opening. Where shotcrete is used as the final lining for tunneling projects, durability is usually a primary concern and, therefore, accelerator type and dosage should be selected and accelerator applied so that service life, durability (Zhang et al. 2016), and long-term performance is not compromised, and long-term maintenance issues do not develop.

Accelerated shotcrete develops more heat than non-accelerated shotcrete. Thermal expansion and subsequent contraction cracking and shrinkage cracks need to be taken into consideration, especially for final lining applications.

Due to the variability in chemical composition, accelerators may perform differently depending on the specific cement used. Observations of setting times based on shotcrete test panels for specific cement-admixture combinations provide a more consistent and reliable indication of actual performance under field conditions (Prudencio et al. 1996).

As with all chemical reactions, the rate of cement hydration increases with temperature. Hot or cold shotcrete placement conditions have a significant effect on setting times. Some mine temperatures are high due to geothermal gradients. At high temperatures, setting times may be significantly reduced, whereas at cold temperatures, the cement hydration reaction may barely initiate. Surface and near-surface structures may experience cold conditions during winter construction. Adding additional accelerator to shotcrete in these conditions does not necessarily resolve this situation because the reaction is temperature-dependent, and such an addition may significantly detract from the long-term durability of the shotcrete and its reinforcing elements.

Storage of accelerators, especially liquid accelerators, may be a challenge on underground projects. The performance of some accelerators is highly impacted by the environmental temperature. Insulation of storage containers may therefore be necessary. In addition, some liquid accelerators have the tendency to settle and must be constantly agitated to stay homogeneous.

Accelerator admixtures used in wet-mix shotcrete are usually added in liquid form at the nozzle along with the compressed air. Accelerator admixtures for dry-mix shotcrete are usually in powder form that can be preblended into the mixture. These oven-dried, preblended shotcrete materials can be stored in a dry environment and used without detrimental effect on their performance for up to 1 year. When moist aggregates are used with the dry-mix method,

the accelerator should not be in contact with the damp cement and aggregates for longer than a few minutes before application, or significant pre-hydration will take place. This may result in increased rebound, sloughing, reduction in bond, and short- and long-term strength loss. Addition of liquid accelerators at the nozzle, concurrent with the addition of the mixture water, may also be used with the dry-mix method.

When liquid accelerators are used, metering pumps coupled to the mixture feed inject the right amount of accelerator into the water stream to the nozzle for the dry-mix application, and into the air stream for the wet-shotcrete method. In dry-mix shotcrete, if a powder accelerator is not pre-blended with the dry ingredients, the accelerator enters the water stream after the pre-dampening takes place. This accuracy and control give the contractor the ability to increase or decrease the amount of accelerator, depending on the tunnel support or groundwater conditions.

The accelerator dosage is typically defined as a percentage of the cement weight. However, especially if using wet-mix shotcrete and liquid accelerators, this value is impractical for the crew on-site. In addition, the accelerator pump rate must be adjusted to the concrete pump rate to achieve a constant accelerator dosage. Ideally, an accelerator pump that is synchronized with the concrete pump should be used for underground applications. The calibration of accelerator dosing pumps should be regularly checked to ensure that the accelerator is introduced to the shotcrete mixture at the desired dosage.

Where groundwater is expected, estimates of inflow and analyses of the potential groundwater chemistry should be made to determine the potential implications on cement type, accelerator performance during application, and on the long-term durability of the shotcrete. The ground and groundwater temperature should also be measured. Hot- or cold-water conditions may affect the setting time and long-term performance of the shotcrete.

It should be noted that, in some instances (particularly in potash mining), brine water is used for shotcrete. In some cases, a higher dosage of accelerating admixture may be needed to initiate setting because the elements in the water may retard hydration. Brine water contains chlorides, however, which sometimes act as set-time accelerators for shotcrete and are very corrosive to steel.

4.2—Recommended specifications

The specifier may cite **ASTM C1436** to cover all the materials used in shotcrete. The types and grades of cement, combined aggregates, admixtures required, and the type, length(s), and diameter(s) or aspect ratio(s) of fiber reinforcement should be specified when using ASTM C1436.

An example of using ASTM C1436 is:

X.1 Materials for shotcrete shall conform to ASTM C1436. Cement shall conform to ASTM C150/C150M, Type I or Type II or Type III. Combined aggregates shall conform to Grading No. 2. It shall be determined by the contractor which admixtures to use to meet the performance requirements of this specification. Fibers shall be

Table 4.2—Example guide specification for shotcrete materials

Section/ Part/ Article	Recommended specification language	Notes to the Specifier
4.1	<i>Cement</i>	
4.1.1	Cement shall conform to ASTM C150/C150M or be of the type specified by the owner.	Usually a Type I, II, or III cement is specified, but other types may be specified under certain circumstances. Type II or other types may require special attention to the accelerator compatibility.
4.2	<i>Supplementary cementitious materials</i>	
4.2.1	Silica fume shall conform to ASTM C1240.	The improvements in shotcrete performance with respect to rebound and maximum achievable buildup by silica fume use are consequences of its particle size and shape. Therefore, for dry-mix shotcrete, silica fume should be used in its undensified form to the extent practicable. Whenever different sources of silica fume exist, preference should be given to those with smaller average particle size (preferably less than 0.008 in. [0.2 mm]). For wet-mix applications in which there is enough mixing action, densified silica fume can be used with equivalent results.
4.2.2	Fly ash shall conform to ASTM C618 Class F or Class C.	The addition of fly ash is acceptable only if all shotcrete performance requirements can be demonstrated during preconstruction testing. Testing for sulfate resistance should be conducted when required. Class F fly ash can help reduce alkali-silica reaction (ASR) in reactive aggregate mixtures.
4.2.3	Slag cement shall conform to ASTM C989/C989M.	The addition of slag cement is acceptable only if all shotcrete performance requirements can be demonstrated during preconstruction testing. This is especially relevant to early strength gain.
4.3	<i>Aggregate</i>	
4.3.1	Aggregate shall be normalweight aggregate conforming to ASTM C33/C33M, except for grading requirements.	Some of the provisions identified in ASTM C33/C33M may be waived by the specifying authority. Aggregates should be clean, sound, and free of potentially deleterious materials.
4.3.2	Coarse aggregate shall have a 3/8 in. (9.5 mm) maximum size and be combined with fine aggregate to produce a combined aggregate grading that meets the ASTM C1436 Grading No. 1 or No. 2 limits as specified by the owner.	Grading No. 2 limits are normally preferred for ground support and linings. Grading No. 1 materials are sometimes used in finish coats and other thin layers.
4.3.3	Lightweight aggregates shall conform to ASTM C330/C330M.	Typically, lightweight aggregates are only used for special shotcrete applications.
4.4	<i>Water</i>	Water shall be as specified in ASTM C1602/C1602M.
4.4.1	All mixing water used for shotcrete shall meet the requirements of ASTM C1602/C1602M.	Recycled mixing water should not be used, to avoid potentially adverse reactions from residual traces of admixtures.
4.4.2	If nonpotable water is used, it shall be free of oil and chemical or organic impurities or any other substances harmful to shotcrete.	
4.4.3	All water used for high-pressure washing of rock surfaces before the application of shotcrete, or used to remove rebound, overspray, surface laitances, and for shotcrete curing, shall be free of oil and chemical or organic impurities deleterious to achieving shotcrete bond.	
4.4.4	Heat water to control the specified in-place shotcrete temperature.	In addition to protecting and heating shotcrete aggregates, the mixture water can be heated to offset some cold weather conditions during shotcrete placement. Appropriate safety measures should be taken with the hot water heating system and the use of hot water during shotcreting. High-pressure stream should not be used to heat and hydrate the shotcrete mixture.
4.5	<i>Admixtures</i>	
4.5.1	Air-entraining admixtures shall conform to the requirements of ASTM C1141/C1141M.	Liquid air-entraining admixtures are typically used in wet-mix shotcrete.
4.5.2	Water-reducing, set-retarding, and hydration-controlling admixtures shall conform to the requirements of ASTM C1141/C1141M.	Mid-range water reducers have been used to achieve required slumps. They have also been used in conjunction with high-range water reducers to increase the slump while pumping distances over 1000 ft (300 m), without changing the water-cementitious materials ratio (w/cm).
4.5.3	High-range water-reducing admixtures shall conform to the requirements of ASTM C1141/C1141M.	To enable wet-mix pumpability at a cement content of approximately 750 lb/yd ³ (450 kg/m ³) and w/cm below 0.45, use of a high-range water-reducing admixture is usually necessary to achieve a slump of approximately 3 in. (80 mm). Mid-range water reducers have been used to achieve the same required slump. They have also been used in conjunction with high-range water reducers to increase the slump while pumping distances over 1000 ft (300 m), without changing the w/cm .

Table 4.2, cont.—Example guide specification for shotcrete materials

4.5.4	Shotcrete accelerators shall not be more alkaline than the portland cement used and shall not present a health hazard to the shotcrete crew or other personnel.	Refer to the extended discussion of accelerators in Section 4.1.
4.5.5	Hydration-stabilizing admixtures shall conform to the requirements of ASTM C494/C494M. If hydration-stabilizing admixtures are used in combination with accelerating admixtures, both need to be tested during the preconstruction, tested to evaluate potential performance impact, and verify admixture compatibility.	Hydration-stabilizing admixtures are used to limit prehydration of wet- and dry-mix shotcrete and to extend the retention time of batched shotcrete when the handling and logistical constraints typically associated with underground construction cause prolonged transport and discharge time.
4.5.6	The introduction of admixtures shall be limited to the types specified and shall be added in the prescribed manner and dosage approved by the owner. Admixtures containing chlorides shall not be used where the shotcrete contains structural elements, such as reinforcing bar.	The addition or adjustment of all specified admixtures shall be documented in accordance with the project quality assurance and quality control requirements. The geological, tunnel stability, or groundwater conditions necessitating use of additional accelerating admixtures should be duly recorded by the owner and contractor. The quantities of accelerator used in these locations and conditions should be recorded.
4.6	<i>Fibers</i>	
4.6.1	Steel fiber	Steel and macrosynthetic fibers are used in underground shotcrete with the primary objective of providing post-crack reinforcement. One advantage of fiber over welded wire reinforcement is related to execution time and to less shotcrete spent covering the welded wire reinforcement and filling the rock contours caused by irregular overbreak. The use of fibers in shotcrete also leads to a reduction in the number and width of shrinkage cracks that may eventually lead to water leakage (Campbell 1999). Other types of ASTM A820/A820M steel fibers may be applicable.
4.6.1.1	Steel fiber shall conform to ASTM A820/A820M and be suitable for production of ASTM C1116/C1116M Type I steel fiber-reinforced shotcrete.	
4.6.1.2	Steel fiber shall be bent or deformed low-carbon, cold-drawn steel wire, Type I, with a minimum tensile strength of 160,000 psi (1100 MPa), a minimum length between 1 and 1.375 in. (25 and 35 mm), and a minimum aspect ratio of 40.	
4.6.1.3	Steel fiber shall be free of oil, grease, corrosion, or other contaminants.	Microsynthetic fibers, used at 0.1 to 0.2% by volume, are known to reduce plastic shrinkage cracking of shotcrete and mitigate explosive spalling effects in fire. Macrosynthetic fibers, at dosages of 0.5 to 1% by volume and at high deflections, can provide a high post-crack load-carrying capacity (Bernard 2013, 2019).
4.6.2	Synthetic fiber	
4.6.2.1	Synthetic fiber shall be a type suitable for production of ASTM C1116/C1116M Type III synthetic fiber-reinforced shotcrete.	

Table 5.1—Support functions of composite ground support components (after Kaiser et al. [1996])

Support characteristics	Reinforcing	Retaining	Holding
Stiff	Grouted reinforcing bar	Shotcrete	Grouted reinforcing bar
Soft	—	Welded wire reinforcement	Long mechanical bolt
Strong	Cable bolt	Reinforced shotcrete	Cable bolt
Weak	Thin reinforcing bar	No. 9 (3.35 mm diameter) gauge welded wire reinforcement	Split set
Brittle	Grouted reinforcing bar	Plain shotcrete	Grouted reinforcing bar
Yielding	Cone bolt	Chain-link mesh	Yielding rock bolt

steel, Type I, deformed, and shall be 1 to 1.375 in. (25 to 35 mm) long, with a minimum aspect ratio of 40.

Alternatively, each component may be specified in the contract documents. Recommended specifications for individual materials are provided in Table 4.2. The information is provided in a guide specification format: the left column provides the recommended specification language, and the right column provides notes to the specifier.

CHAPTER 5—ANCHORAGE AND REINFORCEMENT

5.1—Composite support systems

The term “composite support” is used when two or more components of support are used. Many composite systems use shotcrete as one of the components (Table 5.1). The shotcrete may act in any of three ways:

(1) **Sealing:** Thin layer of shotcrete (typically 1 to 2 in. [25 to 50 mm]) seals off the soil or rock surface to avoid exposure to the elements and prevent or mitigate deterioration of the soil or rock.

(2) **Bridging:** Thicker layer of shotcrete (typically 3 to 5 in. [75 to 125 mm]) acts as a member to support soil and loose rock between main support members (rock anchors, steel sets) and to collect and transfer load to the main support members; often combined with mesh and optional lattice girders.

(3) **Arching:** Thick layer of shotcrete (typically 4 to 12 in. [100 to 300 mm]) acts as the main structural member and creates a structural arch in soft ground or very weak rock conditions; often combined with mesh and/or lattice girders. In the design, the sealing layer becomes typically an element of the shotcrete arch.

5.2—Shotcrete with pattern rock bolts or anchors

Shotcrete used with rock bolts is primarily used to protect the rock surface from weathering (refer to “(1) **Sealing**” in Section 5.1). In some cases, the shotcrete with welded wire reinforcement and reinforcing waler bars may actively act as lagging between rock anchor members (refer to “(2) **Bridging**” in Section 5.1). Figures 5.2a and 5.2b are photographs of rock bolts; Fig. 5.2c shows a tunnel with pattern bolting, photographed just before shotcreting.



Fig. 5.2a—Rock bolt installation.



Fig. 5.2b—Rock bolts and grout.



Fig. 5.2c—Tunnel with pattern bolting before shotcreting.

5.2.1 Thickness of shotcrete layer—The thickness of the shotcrete will be determined by the design engineer considering the function required of the shotcrete.

5.2.2 Timing of rock bolt and shotcrete application—In poor ground conditions, shotcrete should be applied immediately after excavation. With robotic placing arms, quick application of shotcrete may temporarily stabilize the heading, with rock bolting to follow immediately. Additional shotcrete may be placed later, when the crown and walls have stabilized.

As with all shotcrete applications, the bond that develops between the shotcrete and rock is of great importance. A shotcrete layer that is delaminated from the rock due to poor bonding will not be effective in controlling rock mass displacements (refer to [Chapter 16](#)). The application of shotcrete can mitigate the risk of smaller rocks from shifting and/or falling and thus keep larger rocks locked in place.

5.3—Shotcrete with rock bolts, friction stabilizers, and welded wire reinforcement

Where welded wire reinforcement is included as a component of a rock bolt and shotcrete support system, shotcrete application can become difficult under certain conditions. This typically occurs when limited pattern bolting and relatively thin layers of shotcrete are specified for moderately blocky to very blocky ground, and where drill-and-blast excavation methods are used. The profile irregularities produced under such conditions typically result in an increased number of rock bolts to force the welded wire reinforcement tight to the rock surface profile. Figure 5.2c is a photograph of a drill and blast tunnel with rock bolts and welded wire reinforcement. When installed, the welded wire reinforcement tends to be in contact only with the protruding blocks or asperities and leaves voids, or requires excessive shotcrete infilling behind the welded wire reinforcement in areas of greater overbreak.

Where specifications stipulate that the welded wire reinforcement should be covered by a minimum layer of shotcrete, substantial volumes of shotcrete are required to fill voids and overbreak. If insufficient rock bolts are used to secure the welded wire reinforcement, then shotcrete tends to vibrate the loose welded wire reinforcement, making shotcrete application difficult. This can be remedied by the use of supplemental pins or short rock bolts 1.5 ft (0.5 m) in length, which avoids the need for full-length rock bolts to secure welded wire reinforcement.

In civil tunneling applications, where a final lining is typically installed later, the initial lining must be brought to a predefined profile. Shotcrete placed into overbreak and the payment thereof should therefore be clearly regulated in the contract to avoid disputes.

5.3.1 Type of welded wire reinforcement—A stiff 4 x 4 in. (100 x 100 mm) or 6 x 6 in. (150 x 150 mm) welded wire reinforcement is typically used for underground support. Lightweight, chain-link mesh is not recommended for use as shotcrete reinforcement. Excessively stiff welded wire reinforcement is difficult to handle and form when overbreak or asperities are encountered. This can result in loose



Fig. 5.3.2—Wire mesh in tunnel with considerable overbreak.

welded wire reinforcement, which requires additional rock bolts to secure the welded wire reinforcement and the addition of excess shotcrete where the distance between the rock and welded wire reinforcement is more than a few inches. If chain-link fabric is used to stabilize rubble or gouge, it should not be included in the design. Additional welded wire reinforcement or reinforcing waler bars should be used to add tensile strength to the shotcrete lining. If the welded wire reinforcement is structurally used in the design, sufficient overlap in radial but also longitudinal direction should be specified. If possible, longitudinal and radial overlaps at the same location should be avoided by offsetting the overlaps.

5.3.2 Placing and securing welded wire reinforcement—The welded wire reinforcement should be firmly tied to the rock reinforcement before shotcrete application so that wire vibration does not lead to debonding and voids. Additional fixture bolts should be used to tighten the welded wire reinforcement when required and to form it into areas of overbreak. Care should be taken to ensure that rebound is not trapped behind the welded wire reinforcement, and that overbreak areas are not filled so rapidly that debonding occurs. Figure 5.3.2 illustrates welded wire reinforcement installed in a tunnel with considerable overbreak.

5.3.3 Welded wire reinforcement placement—Placement can be determined empirically or by a structural analysis of the composite shotcrete/welded wire reinforcement liner using tools similar to those used in conventional reinforced concrete analysis.

5.4—Fiber-reinforced shotcrete

Alternatives to welded wire-reinforced shotcrete are available in the form of fiber reinforcement. Figures 5.4a through 5.4c show varieties of steel fibers and macrosynthetic and microsynthetic fibers, respectively. Steel and macrosynthetic fibers are primarily used for structural purposes, whereas microsynthetic fibers mitigate shrinkage cracking and spalling behavior in case of fires. Structural fibers are typically used to avoid the potential problems associated with the installation of welded wire reinforcement or when used as sealing shotcrete. The advantages of these materials include labor and time savings, materials reduction, and increased safety because workers are not required under unsupported

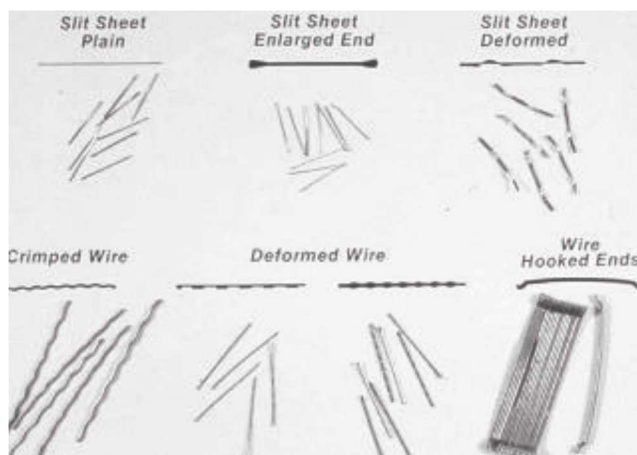


Fig. 5.4a—Close-up of steel fibers.

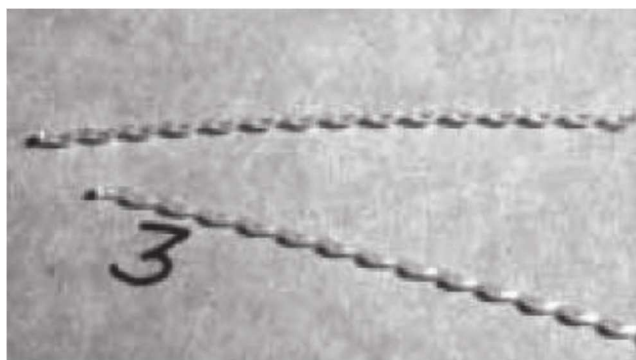


Fig. 5.4b—Close-up of macrosynthetic fibers.

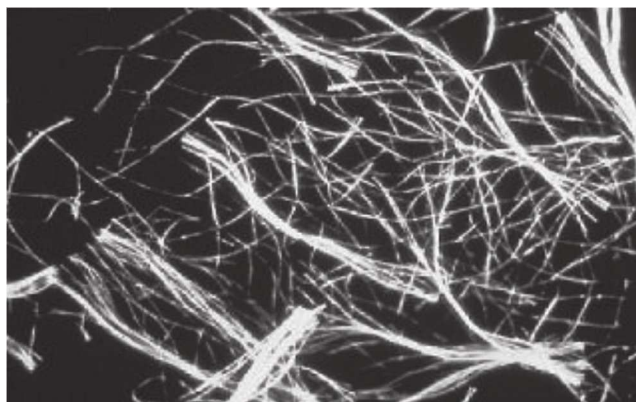


Fig. 5.4c—Close-up of microsynthetic fibers.

ground to attach welded wire reinforcement. In highly stressed ground, it may be necessary to reduce the induced stresses imposed on the excavated opening by allowing controlled displacement of the opening. A thin, 1 to 2 in. (50 to 75 mm) layer of fiber-reinforced shotcrete (sealing) can control superficial degradation, such as spalling and raveling of the excavated surface, while providing temporary support.

Steel fibers have been used since the early 1970s in underground support applications. Steel fibers are typically used at the rate of 40 to 100 lb/yd³ (25 to 60 kg/m³) (0.45 to 0.76 vol.%) to provide post-cracking load-carrying capability (sometimes called residual strength) to meet the specified performance requirements. Steel fibers impart to

the shotcrete lining the ability to redistribute cracking by providing miniature plastic hinges, and thus redistribute the moments and stresses resulting in increased load capacity (Vandewalle and Bekaert 2005).

Macrosynthetic fibers have been increasingly used in underground support applications that require a large deformation of the lining, such as in deep hard-rock mining. Addition rates are typically 10 to 25 lb/yd³ (6 to 15 kg/m³) for these applications. Fiber material is typically polypropylene or copolymers of the polyolefin family. Fiber length is typically 1.75 to 2.25 in. (45 to 55 mm), with diameters in the 0.03 in. (0.8 mm) range.

Microsynthetic fibers are used to provide plastic shrinkage cracking control and resistance to explosive spalling in linings that may be subjected to rapid temperature rise, such as in hydrocarbon-fueled fires. Addition rates are typically 1.5 lb/yd³ (0.9 kg/m³) for plastic shrinkage control, and 3 lb/yd³ (1.8 kg/m³) for explosive spalling mitigation. Fibers for explosive spalling protection should be 0.0013 in. (32 μ m) or less in diameter, and approximately 0.5 in. (12 mm) long.

Unreinforced shotcrete subjected to the same stresses may crack and lose capacity as a result of yielding. The post-crack ductility and residual load-carrying capacity of fiber-reinforced shotcrete may be used effectively to accommodate tunnel displacement while retaining adequate support capacity of the shotcrete lining system. The engineer should select the appropriate fiber-reinforced shotcrete toughness and thickness to provide appropriate post-crack loading capacity and lining stiffness (Kaiser et al. 1996; Kirstin 1983; Morgan et al. 1999a; Papworth 2002; Grimstad et al. 2002).

5.5—Shotcrete with lattice girders

Lattice girders are arch structural members made of bars with an open lattice. The girder can provide initial support for openings and allow placement of a thick shotcrete lining that acts as a concrete arch. The shotcrete between the girders acts as lagging between these concrete arches. Figures 5.5a through 5.5c are close-up photographs of a typical lattice girder before and during shooting; Fig. 5.5d is a photograph of a tunnel with lattice girders installed and ready for shotcreting.

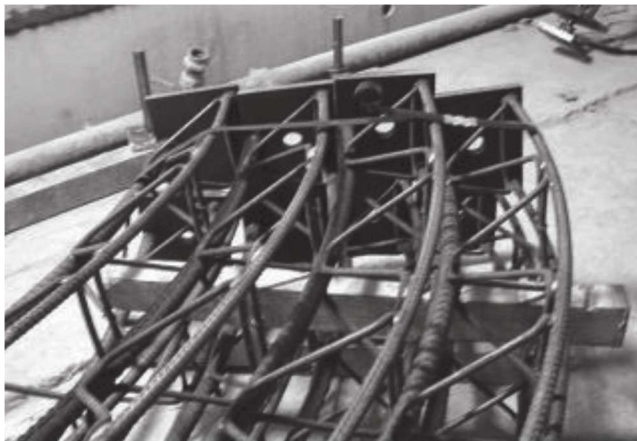


Fig. 5.5a—Close-up of a typical lattice girder.

5.5.1 Size and spacing—Lattice girders can be manufactured with different bar sizes and sizes of spacers for lattices to provide a section modulus that meets the tunnel support requirements.



Fig. 5.5b—Typical lattice girder during shooting (robotic).



Fig. 5.5c—Typical lattice girder during shooting (manual).



Fig. 5.5d—Tunnel with lattice girders.

5.5.2 Installation and shotcrete application—Lattice girders are installed before shotcrete or after the application of a thin layer of sealing shotcrete that is placed to prevent raveling. Typically, one lattice girder per excavation round is installed with sufficient distance from the face to not hinder the following excavation. Available support pressure increases as shotcrete is applied in and around the lattice girder, and it continues to increase as the shotcrete cures and develops strength. If welded wire reinforcement is used, lattice girders are used to keep the welded wire reinforcement in place.

5.5.3 Shotcrete placement—Care should be taken to avoid trapping rebound and leaving pockets behind the reinforcing bars that form the lattice girder. It is important that the lattice girder be fully encapsulated, which may require shotcrete application from several different shooting positions. In addition, to be fully effective, the gap between the ground and the lattice girder must be properly filled with shotcrete to provide proper load transfer and avoid the provision of a pathway for water.

5.6—Shotcrete with conventional steel sets

Steel sets may also be enhanced by the use of shotcrete, mostly in mining applications. A steel arch support transfers its load-carrying capacity to the rock by blocking. The wider the blocking, the more moment stress is placed on the steel set. Figure 5.6 is a photograph of steel sets with significant wood blocking that illustrates how wood blocking transfers irregular loading conditions to the steel set. In theory, the maximum support is attained when continuous blocking is achieved. Shotcrete or concrete embedment of steel arches meets the continuous blocking requirement. The shotcrete lining also acts as a corrosion inhibitor to the steel arch support.

Steel sets may be lagged with shotcrete, such that the shotcrete is used to fill the gap between the steel sets.

The extent of the loading on the steel sets is a direct consequence of the method of excavation, support installation, and long-term rock support interaction. Traditional steel set designs are based on the inevitable development of a rock

load of some magnitude being imposed by gradual deterioration of the rock mass over time.

When combined with shotcrete and rock bolts, steel sets can provide substantial support capacity that is equivalent to most concrete lining structures. Support installation usually takes place using phased or staged installation sequencing of the ground support. The initial application of shotcrete is usually applied to provide personnel protection and takes place immediately after excavation. Overbreak, voids, and profile irregularities are usually filled and smoothed out. Rock bolt or anchor installation is in the form of pattern bolting or spot bolting used to supplement the initial shotcrete application. Steel sets are then installed and may be backfilled and lagged with shotcrete such that shotcrete is used to fill the gap between the steel set and rock or initial support.

Though feasible, the simultaneous installation of steel set, rock bolts, and shotcrete at the tunnel face is difficult because so much equipment is required. Steel sets are commonly used in conjunction with wood lagging.

5.7—Recommended specifications

Recommended specifications for anchors and reinforcement are provided in Table 5.7. The information is provided in a guide specification format: the left column provides the

Table 5.7—Example guide specification for anchors and reinforcement

Section/ Part/ Article	Recommended specification language	Notes to the Specifier
5.1	Shotcrete anchor bolts or dowels	Consider the provisions cited in ACI 318.
5.1.1	Shotcrete anchor bolts or dowels shall be made from ASTM A615/A615M Grade 60 (420) steel or equivalent as specified by the owner.	Steel grade may be 60 or 80 (420 or 550).
5.1.2	Shotcrete anchor bolts or dowels shall be of the type, diameter, and length specified in the contract documents.	
5.1.3	Provide shotcrete anchor bolts or dowels with attachment means to the shotcrete.	Means may be plate with nuts, hook ends, plates with reinforcing bar spiders, or welded studs.
5.1.4	Provide level pads for the anchor plates as specified in the contract documents.	
5.1.5	Provide rock bolt and anchor bolt setting grout as specified in the contract documents.	
5.2	<i>Reinforcement</i>	
5.2.1	Welded wire reinforcement shall be of the type specified in the contract documents and shall conform to ASTM A185/A185M.	



Fig. 5.6—Steel sets with significant wood cribbing.

Table 5.7, cont.—Example guide specification for anchors and reinforcement

5.2.2	Deformed steel reinforcement for ribs and lattice girders and structural reinforcement shall conform to ASTM standards (or as defined in the Structural Steel Section) and be of the type, size, and strength specified in the contract documents.	Lattice girder specification example: “Each of the primary retaining bars of a lattice girder segment shall be composed of only one piece of high-strength steel of 60 ksi (415 MPa) yield strength or more. The connecting elements at the end of lattice girder segments shall be constructed of angled structural steel having yield strength of 36 ksi (250 MPa) or more.”
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recommended specification language, and the right column provides notes to the specifier.

CHAPTER 6—MATERIALS HANDLING AND STORAGE

6.1—General

The provisions for handling and storage of constituent shotcrete materials should mandate that the materials are not damaged or deteriorated before use. Appropriate consideration of possible moisture or contaminant penetration of the shipping containers should be taken, as well as the temperature of the materials at the time of use. Materials,

such as aggregates, should be stored and handled to limit segregation and to maintain relatively uniform moisture content. Bagged and bulk cement should be stored in such a way as to avoid pre-hydration. Liquid admixtures should not be allowed to freeze, and if they are in the form of suspensions or nonstable solutions, agitating equipment should be provided. Accelerators are especially sensitive and have been discussed in detail in [Section 4.1](#).

6.2—Temperature considerations

Difficulties can be encountered for underground support shotcrete if the temperature of the shotcrete materials is allowed to become excessively low or high. At shotcrete temperatures below 40°F (5°C), the amount of rebound can increase markedly, and the setting and strength development can be seriously slowed. This can result in delays in ground support, inadequate bond between the shotcrete and the application surface, increased accelerator consumption, or a combination of these. The overall quality of the in-place shotcrete will then be reduced and can subsequently lead to safety hazards. Therefore, during cold weather, constituent shotcrete materials should be stored in warm enclosures whenever possible. In addition, heated water should be used in the batching or shooting process to enhance and control the hydration process. Specifications should include a temperature range outside of which a batch should be rejected.

In contrast, temperatures above 85°F (30°C) can lead to an accelerated setting flash set and to a lower long-term strength of hardened shotcrete. Furthermore, if the high temperature is accompanied by a low relative humidity, wet-mix shotcrete can rapidly lose workability, thus reducing the period

Table 6.3—Example guide specification for material handling and storage

Section/ Part/ Article	Recommended specification language	Notes to the Specifier
6.1	Materials handling and storage	As a general note, it should be stated in the specification that all materials should be stored in conformance with the manufacturer's recommendation unless more stringent requirements are cited in the contract specification.
6.1.1	Store portland cement and supplementary cementitious materials to protect from exposure to moisture.	In the case of packaged, preblended, dry, combined material used for shotcrete, adequate protection from humidity should be provided to prevent premature cement hydration, which would ruin the material.
6.1.2	Stockpile and handle aggregates to prevent segregation. Maintain fine aggregate within a 3 to 6% moisture content range. Use shelters or tarpaulins to protect aggregate stockpiles during periods of wet or cold weather.	Wide ranges in the moisture content of shotcrete aggregates should be avoided. This may require storage of aggregates in sheltered enclosures or under tarpaulins, particularly for volumetrically batched shotcrete. Variable moisture content will result in an irregular quality of the in-place shotcrete. Moreover, excess moisture content can result in aggregates that bridge over gates in hoppers and erratic aggregate feed, resulting in variable shotcrete mixture proportions.
6.1.3	Storage areas shall maintain shotcrete aggregates above 40°F (5°C) and below 85°F (30°C) whenever possible.	Refer to Section 6.2.
6.1.4	Store fibers in dry, sealed container until ready for batching. Fibers shall be free from corrosion, oil, grease, or other contaminants.	Care should be taken to see that fibers are stored in a manner that will prevent their deterioration or the intrusion of moisture or foreign matter. It may be necessary to cover the shipping containers with tarpaulins. Refer to ACI 544.3R.
6.1.5	Control temperature of components such as rock bolts, steel sets, or lattice girders within the 40 to 85°F (5 to 30°C) range.	Refer to Section 6.2.
6.1.6	Liquid admixtures, especially accelerators, shall be stored and protected from the environment, cold weather, freezing and periodically agitated per the manufacturer's recommendations.	Refer to Sections 4.1 and 6.1.



available between batching and discharging the shotcrete. For both dry-mix and wet-mix shotcrete, low or high temperature combined with a low relative humidity can increase the potential for plastic and early drying-shrinkage cracking. In hot underground environments, particularly mines at depth, the inclusion of hydration-controlling admixtures in a wet-mix design is strongly recommended.

6.3—Recommended specifications

Recommended specifications for material handling and storage are provided in Table 6.3. The information is provided in a guide specification format: the left column provides the recommended specification language, and the right column provides notes to the specifier.

CHAPTER 7—SHOTCRETE MIXTURE PROPORTIONING

7.1—General

Equipment and placement techniques have an impact on the properties, placement, and performance of the shotcrete mixture. Shotcrete mixtures should therefore be developed and tested under field conditions during the preconstruction period because it is essential that sufficient confidence is developed in the mixture before construction and that any potential problems are effectively recognized and eliminated. Mixture proportions are usually developed in one of two ways: by trial batching and test panels, or based on historical data.

7.2—Mixture proportions by trial batching or historical data submissions

The development of trial batches should be planned well in advance of construction to permit the timely development of shotcrete mixture proportions, QA review, and acceptance of submittals. The preconstruction testing should simulate the

actual construction conditions (materials, equipment, crew, procedures, environmental conditions) as much as possible. Performance requirements guide the mixture proportions. Mixture proportions and component materials that have no previous documented use are usually supported by test data that verify material properties, mixture proportions, field conditions, test data, and performance-related information.

Adjustments can be made to trial shotcrete mixture proportions during production and may provide an opportunity to optimize mixture proportions to satisfy specific requirements or properties.

If materials and mixture proportions used on previous underground projects have demonstrated a capacity to satisfy current project requirements, documentation of past performance may be acceptable to the owner. A complete historical data submittal should include, at a minimum, all material data, mixture proportions, project conditions, test reports, data summaries, and analyses. This approach may reduce or eliminate the need for extensive preconstruction testing.

Shotcrete properties are often considered the same as those of ordinary concrete having the same proportions. The pneumatic application of these materials, however, modifies the distribution and the initial proportions of the constituents due to phenomena such as rebound, compaction, and preferred orientation of fibers, and other, when used. These phenomena should be considered because they affect the properties of the in-place shotcrete. For the wet-mix process, a relatively low amount of rebound is expected; it mainly depends on the shooting position, orientation, technique, and mixture composition (an average of 5% on vertical surfaces, and 15% on overhead surfaces [Morgan and Pigeon 1992]).

7.3—In-place mixture proportions

The in-place mixture proportions can vary substantially from the as-batched proportions, especially for dry-mix or for fiber-reinforced shotcrete. Figure 7.3 is a set of measure-

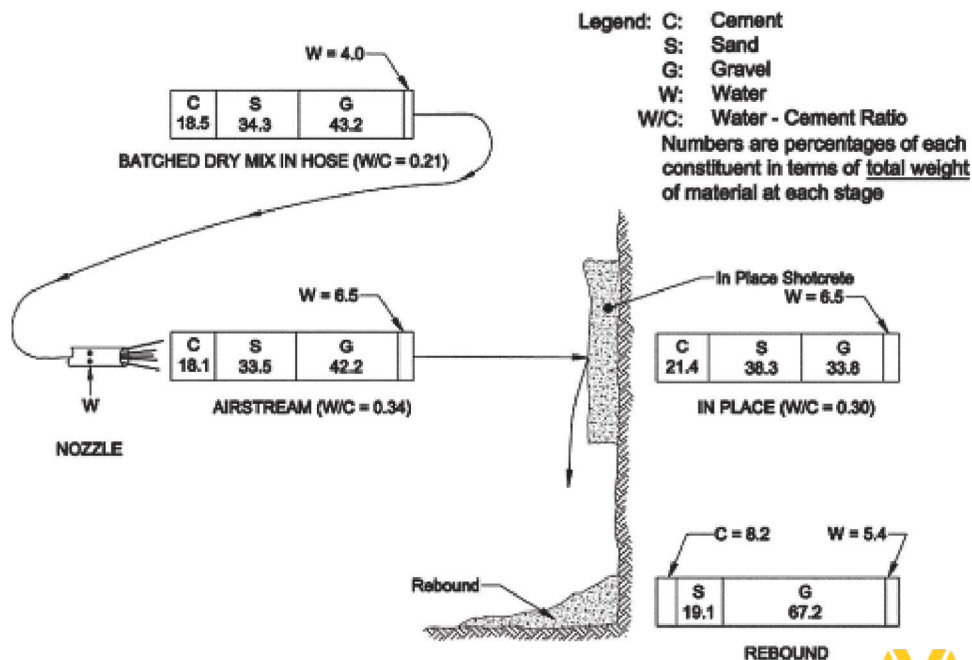


Fig. 7.3—Measurements of the percentage of various dry-mix components before and after shooting.

ments of the percentage of the various components before and after shooting dry-mix shotcrete measured in one research project (Parker 1976). Because the larger aggregate particles rebound more than the smaller ones, the larger the amount of rebound, the greater the proportion of cement and sand in the in-place shotcrete will be when compared with the as-batched proportions. The combined use of fiber-reinforced shotcrete together with wire mesh should be avoided because proper embedment of the mesh is an issue. Note that the rebound of steel fibers may vary from 35 to 80% by mass for dry-mix shotcrete, and from 10 to 20% by mass for wet-mix shotcrete, depending on shooting orientation, materials, and geometry and length of the fibers (Banthia et al. 1994). Rebound of some synthetic fibers in wet-mix shotcrete can be negligible.

The composition of a shotcrete mixture should be proportioned and adjusted to ensure its resistance to weathering, its compatibility with hydro- and geo-chemistry, and its meeting or exceeding the project's design durability, strength, and strength-gain requirements. The water-cementitious materials ratio (w/cm) (strength and durability), amount of entrained air (freezing-and-thawing resistance), silica fume (adherence, permeability, and durability), steel or macrosynthetic fibers (ductility and toughness), and aggregate grading are some of the parameters that will need to be adjusted. The initial composition of a shotcrete mixture should also be formulated to optimize shotcrete projection and placement. Generally, this optimization is achieved by raising the proportion of cementitious materials by reducing the proportion and size of the coarse aggregates and by adding silica fume. Temperature plays an important part in this phenomenon.

7.4—Dry-mix shotcrete

In the case of the dry-mix process, determining the exact amount of water added is difficult because it is regularly adjusted by the nozzleman according to the placing conditions. It should be noted, however, that the w/cm is generally between 0.35 and 0.45. For this reason, the proportions of a shotcrete mixture are often expressed as a percentage of the mass of the dry constituents. If a nominal w/cm is assumed, materials are proportioned in the same manner as for conventional concrete. Table 7.4 shows examples of mixture compositions expressed according to these two methods. Figure 7.4a presents the data in Table 7.4 graphically.

Dry-mix shotcrete is usually proportioned for 20% of cement by mass of dry materials (equivalent to 705 lb/yd³ [420 kg/m³]) when a 0.40 w/cm is assumed). For underground applications, coarse and fine aggregates are usually blended to obtain a smooth curve for the ACI No. 2 grading (ACI 506R). Coarse aggregate is essential to high-quality shotcrete, but because coarse aggregates tend to rebound more than sand, the maximum aggregate size is usually limited to 10% retained in the 3/8 in. (9.5 mm) sieve, and 100% passing the 1/2 in. (12.5 mm) sieve. Packaged, preblended, dry, combined materials for use in shotcrete should meet the requirements of ASTM C1480/C1480M.

Undensified silica fume is normally used in dry-mix shotcrete to reduce dust, fiber, and aggregate rebound, and to permit a greater maximum overhead buildup (Pigeon et al. 2000). The silica fume content is usually between 8 and 12% by mass replacement of cement. A 20% by mass cementitious content is maintained.

Whenever packaged, preblended, dry-combined materials are used, powdered accelerating admixtures may be added to the dry materials during the packaging operations. The usual dosage may vary from 2 to 5% by mass of cement, depending on the type of accelerator and the application. Higher accelerator dosages (up to 6%) can be used for extreme cases of unstable ground. Higher doses, however, especially if greater than 6%, may have an adverse effect on the ultimate strength and durability. The accelerator supplier

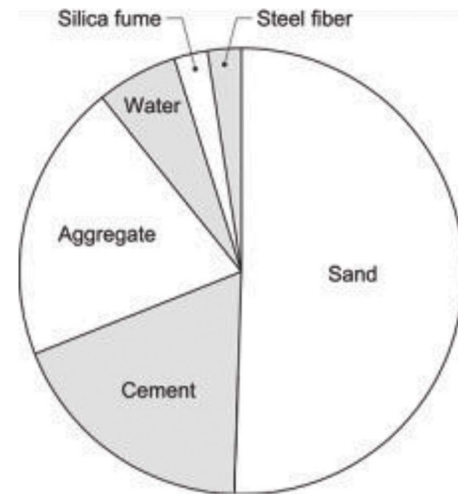


Fig. 7.4a—Typical mixture design for dry-mix underground shotcrete (percent by weight).

Table 7.4—Typical compositions of underground dry-mix concrete mixture proportions

Constituents	Usual quantities	Fiber-reinforced shotcrete with silica fume	
		lb/yd ³	kg/m ³
Water	According to placing conditions	316	188 (for $w/cm = 0.40$)
Cement	18 to 22% by mass of dry materials	705	420
Silica fume	0 to 15% by mass of cementitious materials	85	50
Sand	50 to 80% by mass of dry materials	2025	1200
Coarse aggregate (maximum 1/2 to 3/8 in. [9.5 to 12.5 mm])	0 to 25% by mass of dry materials	675	400
Steel fibers	Up to 1% by volume	50	50