

Guide for Specifying Underground Shotcrete

Reported by ACI Committee 506



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Guide for Specifying Underground Shotcrete

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Guide for Specifying Underground Shotcrete

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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 and tunnel support systems; mixing and placement equipment; mixture proportioning; preconstruction and construction testing; quality assurance; quality control; safety; shotcrete; shotcrete application.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Shotcrete, the method of spraying concrete onto a surface, is ideally suited for the support and construction of underground excavations in earth and rock structures. 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; and resultant strength, durability, and toughness. These qualities are desirable in ground support and lining applications. In North America, shotcrete is conventionally defined as pneumatically applied concrete, while in Europe it is more commonly referred to as sprayed concrete.

Although concrete plays a very important role in underground construction, shotcrete has many advantages over concrete. Final concrete linings for tunnel and underground structures are typically composed of cast-in-place or precast concrete sections that provide a structurally sound and durable subsurface infrastructure. The principal disadvantage with these systems is that they are difficult to install during the excavation phase of tunnel construction. They require formwork or assembly systems that simply cannot be employed in tunnel openings where the immediate concern is ensuring a safe and stable excavation. Accordingly, the cast-in-place lining is often placed after excavation is complete, which results in a much longer time to complete the tunnel.

In contrast, shotcrete in combination with other support elements can provide early and effective ground support and, therefore, a means of ground control necessary for safe, viable, and economic tunnel construction under a wide range of geological conditions.

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. With this gradual evolution in technology and trial and error, came acceptance, adaptation, and new means and methods of successful shotcrete application. The design and placement of shotcrete underground is much more challenging than shotcreting above ground.

Underground construction and shotcrete application are unique and very demanding. The primary focus is worker safety and the need to provide immediate and effective

ground support. Whereas the industry as a whole would accept the performance associated with the compressive strength developed in shotcrete at 28 days, early 8-hour to 1-day strength is critical to the performance of underground shotcrete. Much of the shotcrete is applied overhead to irregular tunnel 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 shotcrete crew. 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.

Tunnel 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. To be viable and acceptable, shotcrete application should be an integral part of the overall cycle. This requires that the shotcrete system as a whole 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, or ramp, and the subsequent use of long and restrictive haulage routes or dropping through a borehole or slickline. This frequently results in extended handling and discharge times. 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 shotcrete as ground support becomes more critical. Finally, the environment is hostile for worker safety, efficiency, and quality control, as well as for quality shotcrete placement and curing conditions. Figures 1.1 to 1.3 illustrate typical conditions at the heading of tunnels and mines.

These types of problems have led to specifically designed systems for batching and handling of shotcrete materials, admixtures, and placement equipment. These systems require significant investment not only in terms of capital, but also in providing experienced supervisory shotcrete and production personnel. 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. Quality assurance, quality control, and the associated inspection and testing activities are equally important in achieving a successful 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 as to ensure that shotcrete specifications are met. The efforts



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

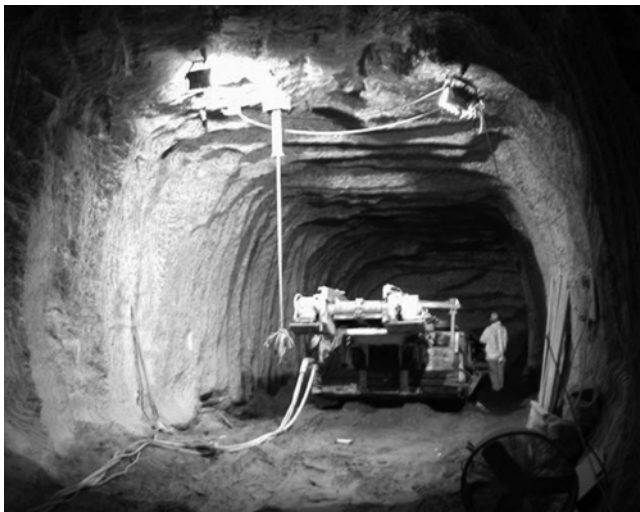


Fig. 1.2—Typical heading: small tunnel with drill jumbo.



Fig. 1.3—Typical heading: mine.

that go into designing, 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. 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.

1.2—Scope

This guide is intended for owner, designer, specifier, and inspection and testing personnel interested in or in need of information and background on the application of underground shotcrete. The guide briefly discusses the concept of composite ground support—the combination of shotcrete and other 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 information 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

Table 1.1—Metrication table

SI to inch-pound	Inch-pound to SI
1 mm = 0.03937 in.	1 in. = 25.4 mm
1 m = 39.37 in. = 3.2808 ft	1/3 yd = 1 ft = 12 in. = 0.3048 m
1 m ³ /min = 35.3147 ft ³ /min	1 CFM = 1 ft ³ /min = 0.0283 m ³ /min
1 m/s = 3.2808 ft/s	1 fps = 0.3048 m/s
1 MPa = 145.0377 psi	1 ksi = 1000 psi = 6.8948 MPa
°C = (°F – 32)/1.8	°F = (1.8 × °C) + 32

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; however, 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 1.1 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

accelerating admixture—an admixture that causes an increase in the rate of hydration of the hydraulic cement and thus shortens the time of setting, increases the rate of strength development, or both.

adit—a horizontal or near-horizontal opening in the ground accessing an underground mine or tunnel.

air lance—refer to **blow pipe**.

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

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

alignment wire—refer to **ground wire** (preferred term).

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)—wood or steel used to fill in and brace between a steel set and the excavated tunnel profile.

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

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

build-up—thickness of applied shotcrete.

concrete pump—an apparatus that forces wet-mix shotcrete to the placing position through a pipeline or hose.

conveying hose—refer to **delivery hose** (preferred term).

cutting screed—sharp-edged tool used to trim shotcrete to the finished outline. (Refer also to **rod**.)

cuttings—shotcrete material that has been applied beyond the finished face and is cut off in the trimming or rodding process.

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

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

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

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

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

gun—dry-mix shotcrete delivery equipment.

gunning—the act of applying dry-mix shotcrete.

hydromix nozzle—a shotcrete hose and nozzle configuration used in place of a predampening system to introduce pressurized water into the material stream via a water ring located approximately 10 ft (3 m) upstream of the nozzle tip. The nozzleman can control the amount of water introduced to the material stream via a control valve near the nozzle tip.

kettle—refer to **boot**.

laitance—a layer of weak material derived from cementitious material and aggregate fines either: carried by bleeding to the surface or to internal cavities of freshly placed mixture; or separated from the mixture and deposited on the surface or internal cavities during placement of the mixture.

macrofiber—a fiber with an equivalent diameter greater than or equal to 0.012 in. (0.3 mm) that is for use in concrete.

material hose—refer to **delivery hose**.

microfiber—a fiber with an equivalent diameter less than 0.012 in. (0.3 mm) that is for use in concrete.

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

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

nozzle operator—the technician who manipulates the nozzle of a placing machine and controls placement of the shotcrete.

overspray—shotcrete material deposited away from intended receiving surface.

owner—the corporation, association, partnerships, individual, or public body or authority with whom the contractor enters into an agreement and for whom the work is provided.

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

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

predampening—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—actions taken by an organization to provide and document assurance that what is being done and what is being provided are in accordance with the contract documents and standards of good practice for the work.

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.

quality control—actions taken by an organization to provide control and documentation over what is being done and what is being provided so that the applicable standard of good practice and the contract documents for the work are followed.

raveling ground—a loss of rock mass cohesiveness that results in degradation of the surface of a tunnel or excavation profile during excavation.

rebound—shotcrete materials, or wet shotcrete that bounces away from the surface against which the shotcrete is being projected.

rock bolts—a reinforcing element, normally made of solid or tube formed steel installed or tensioned with cement or resin grouting in the rock mass.

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

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

sagging—refer to **sloughing**.

screed wire—refer to **ground wire**.

shooting—placing of shotcrete. (Refer also to **gunning**.)

shooting wire—refer to **ground wire** and **screed wire**.

shotcrete—concrete or mortar conveyed through a hose and pneumatically projected at high velocity onto a surface to achieve compaction

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

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

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.

toughness—the energy equivalent to the area under the flexural load-deflection curve up to a specified deflection.

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

water-cementitious material ratio—the ratio of the mass of water, excluding that absorbed by the aggregate, to the mass of cementitious material in a mixture, stated as a decimal and abbreviated as *w/cm*. (Refer also to **water-cement ratio**.)

water-cement ratio—the ratio of the mass of water, exclusive only of that absorbed by the aggregates, to the mass of portland cement in concrete, mortar, or grout, stated as a decimal and abbreviated as *w/c*. (See also **water-cementitious material ratio**.)

wet-mix shotcrete—shotcrete in which the ingredients, including water, are mixed before introduction into the delivery hose; accelerator, if used, is normally added at the nozzle.

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

CHAPTER 3—SUBMITTALS

3.1—Contracts

The contract 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) requirements. Typically, 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 preconstruction, 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, and trained or qualified personnel have met or exceeded the quality requirements identified in the project specifications and drawings. Qualified suppliers or vendors usually provide submittals, which are subject to evaluation before acceptance. Where required, preconstruction testing can support these submittals. Such testing may involve prequalification of processes, materials, equipment, and personnel and applies to shotcrete, concrete, rock bolts, and the manufacture of lattice girders and steel sets. 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, 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.

3.2—Recommended specifications

Recommended specifications for submittals are provided in Table 3.1. 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.

Table 3.1—Example guide specification for submittals

Section/ Part/ Article	Example specification	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	Submit objective evidence that documents detail the qualifications of the work crew, including the supervisor, shotcrete nozzlemen, and shotcrete equipment operator(s).	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.
3.1.2	Submit manufacturer's certification showing source and proof of conformance to project specifications of all shotcrete materials, including: • Portland cement; • Silica fume; • Fly ash and slag cement; • Aggregate source, gradation, bulk density (specific gravity), and absorption; • Water source; • Chemical admixtures with materials safety data sheets (MSDS); and • Fiber reinforcement.	Preconstruction testing results will be required at least 28 days before construction. Consider these additional submittals: • The hot and cold weather precautions necessary to meet project specifications under these circumstances; and • 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: • Rock bolts, rock dowels, and grout; • Anchor plates and spiders; • Anchor hardware (nuts and washers); • Reinforcing steel or welded wire reinforcement; and • Steel ribs or lattice girders.	Consider 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: • 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, accelerator, and all other shotcrete ingredients, in lb/yd³ (kg/m³) or fl oz/yd³ (L/m³) based on SSD aggregates; and • 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 as required. Component material submittals will also be required; refer to Example Specification Section 3.2.1.
3.1.6	Submit proposed methods for mixing, conveying, finishing, curing, and testing along with a complete list of proposed equipment for each task.	Consider these additional submittals: • The shotcrete placement plan; and • 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 description of personal protective equipment, specifically, protective clothing; head, eye, respiratory, and hearing protection; and other safety-related protective devices to be used; • Copies of MSHA form for all employees on project showing their training is up to date, or submit any related OSHA training forms; • Description of procedures for handling all potentially hazardous materials including admixtures, accelerators, and cementitious materials; • Ventilation plan to ensure proper air quality and enhance visibility for nozzleman and crew; and • Plan for monitoring and controlling respirable dust and vapor.	Refer to Chapter 15.

Table 3.1 (cont.)—Example guide specification for submittals

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.

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 where potentially unstable tunnel conditions require immediate and effective ground support to ensure a safe working environment. Accelerators are used whenever an opening is advancing rapidly or where inflowing water is to be controlled. Accelerators are also used to facilitate placement and to enhance the maximum buildup thickness and, hence, minimize shotcrete fallouts, which are not only costly, but also represent a hazard to the underground working crew.

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).

Most accelerators result in lower 28-day strength when compared with a non-accelerated shotcrete mixture. In addition, accelerators often create greater hydrated paste porosity and, therefore, are generally known to reduce shotcrete durability with respect to chloride resistance, permeability, appearance of leaching stains, sulfate attack, and freezing-and-thawing action. For these reasons, quick-setting accelerators should be appropriately prescribed and used. For mining applications, long-term durability may not be a major concern, depending upon the use, location, and projected life of the particular 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 durability is not compromised and long-term maintenance issues do not develop.

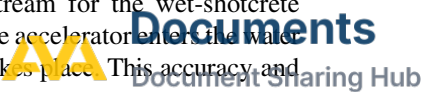
Due to the variability in chemical composition, accelerators may perform differently depending on the specific cement used. Cement-admixture compatibility is usually determined by using a Gillmore needle on cement paste (ASTM C1398). Studies demonstrated that cement-accelerator paste tests have little correlation with the setting times experienced

during actual shotcrete application. 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 cement hydration process is temperature-dependent. 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.

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 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 prehydration 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, the accelerator enters the mix stream after the predampening takes place. This accuracy and



control gives the contractor the ability to increase or decrease the amount of accelerator depending on the tunnel support or groundwater conditions.

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 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, Type I or Type II. 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 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 4.1. 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.

Table 4.1—Example guide specification for shotcrete materials

Section/ Part/ Article	Example specification	Notes to the Specifier
4.1	Cement	
4.1.1	Cement shall conform to ASTM C150 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	Supplementary cementing materials.	
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 a consequence 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.
4.2.3	Slag cement shall conform to ASTM C989.	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	Aggregate	
4.3.1	Aggregate shall be normalweight aggregate conforming to ASTM C33, except for grading requirements.	Some of the provisions identified in ASTM C33 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.

Table 4.1(cont.)—Example guide specification for shotcrete materials

4.3.3	Lightweight aggregates shall conform to ASTM C330.	Typically, lightweight aggregates are only used for special shotcrete applications.
4.4	Water	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 as a means to heat and hydrate the shotcrete mixture.
4.5	Admixtures	
4.5.1	Air-entraining admixtures shall conform to the requirements of ASTM C1141.	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.	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 material ratio (w/cm).
4.5.3	High-range water-reducing admixtures shall conform to the requirements of ASTM C1141.	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 .
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 C1141.	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	Fibers	

Table 4.1(cont.)—Example guide specification for shotcrete materials

4.6.1	Steel fiber	Steel and macrosynthetic fibers are used in underground shotcrete with the primary objective of providing postcrack 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 of a 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.	
4.6.2	Synthetic fiber	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 postcrack load-carrying capacity.
4.6.2.1	Synthetic fiber shall be a type suitable for production of ASTM C1116/C1116M Type III synthetic fiber-reinforced shotcrete.	

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) as a sealing agent to prevent deterioration of the rock; 2) as a member to support the loose rock or soil between rock anchors or arch support sets; or 3) when shotcrete is applied in thick layers (over 3 in. [75 mm]), as a concrete arch member.

5.2—Shotcrete with pattern rock bolts or anchors

Shotcrete used with rock bolts is primarily used to protect the rock surface from weathering. In some cases, the shotcrete with welded wire reinforcement and reinforcing waler bars may actively act as lagging between rock anchor members. Figures 5.1 and 5.2 are photographs of rock bolts; Fig. 5.3 shows a tunnel with pattern bolting, photographed just 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 roof 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).

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

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 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 tunnel profile. Figure 5.3 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 in-filling 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

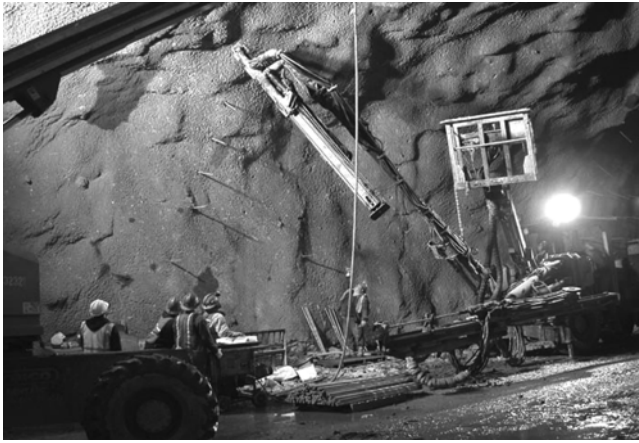


Fig. 5.1—Rock bolt installation.



Fig. 5.2—Rock bolts and grout.



Fig. 5.3—Tunnel with pattern bolting before shotcreting.

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.



Fig. 5.4—Wire mesh in tunnel with considerable overbreak.

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 employed. Lightweight, chain-link mesh is not recommended for use as shotcrete reinforcement. Excessively stiff welded wire reinforcement is difficult to handle and form where overbreak or asperities are encountered. This can result in loose 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.

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 5.4 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 5.5 through 5.7 show varieties of steel fibers and macrosynthetic and micro-synthetic fibers, respectively. These materials are typically used to avoid the potential problems associated with the installation of welded wire reinforcement. The advantages of these materials include labor and time savings, materials reduction, and increased safety, since workers are not required under unsupported ground to attach welded wire

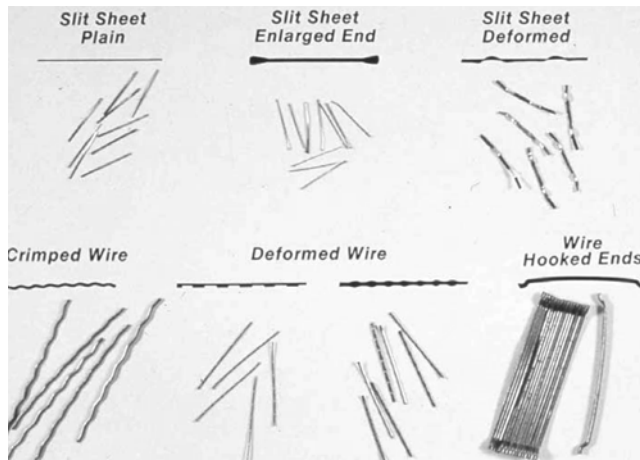


Fig. 5.5—Close-up of steel fibers.

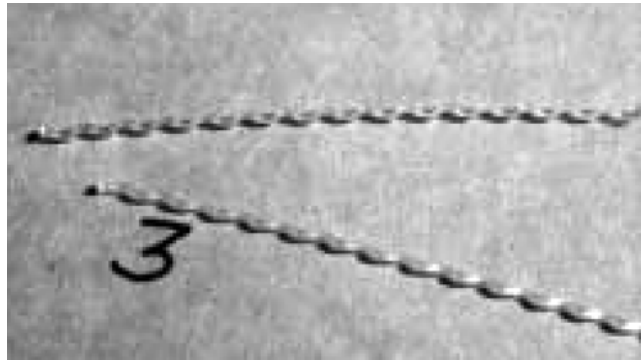


Fig. 5.6—Close-up of macro-synthetic fibers.

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 2 to 3 in. (50 to 75 mm) layer of fiber-reinforced shotcrete can control surficial degradation, such as slaking, 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 60 to 100 lb/yd³ (35 to 60 kg/m³) (0.45 to 0.76 vol.%) to provide postcracking load-carrying capability (sometimes called residual strength). 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

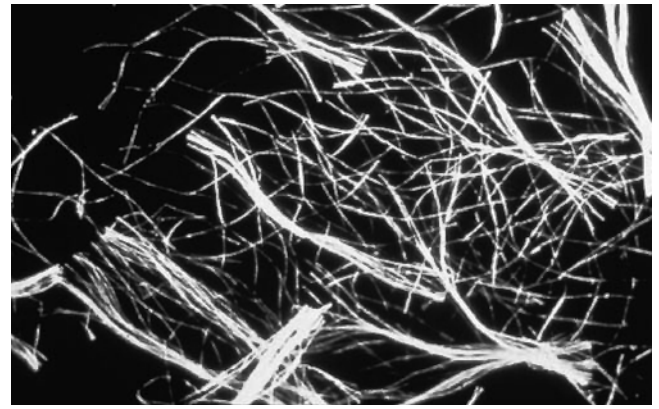


Fig. 5.7—Close-up of micro-synthetic fibers.

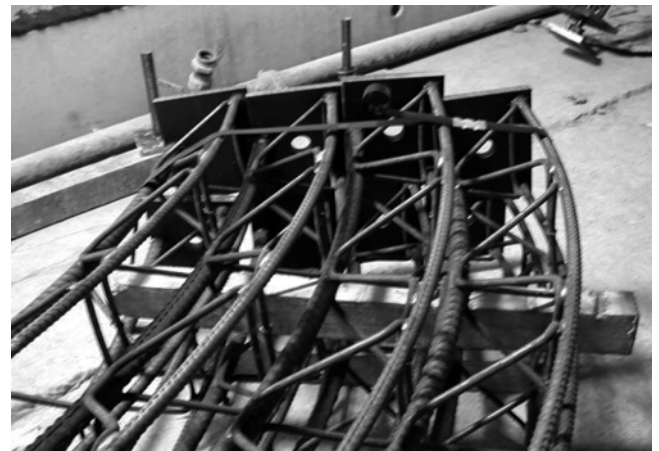


Fig. 5.8—Close-up of a typical lattice girder.

linings that may be subjected to rapid temperature rise, such as in hydrocarbon-fuelled 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 postcrack 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 postcrack 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 5.8 through 5.10 are close-up photographs of a typical lattice girder before and during shooting; Fig. 5.11 is



Fig. 5.9—Typical lattice girder during shooting (robotic).



Fig. 5.11—Tunnel with lattice girders.



Fig. 5.10—Typical lattice girder during shooting (manual).



Fig. 5.12—Steel sets with significant wood cribbing.

a photograph of a tunnel with lattice girders installed and ready for shotcreting.

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.

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. 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.

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.

5.6—Shotcrete with conventional steel sets

Steel sets may also be enhanced by the use of shotcrete. 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 5.12 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

Table 5.2—Example Guide Specification for anchors and reinforcement

Section/ Part/ Article	Example Specification	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 75 (420 or 520).
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	Reinforcement	
5.2.1	Welded wire reinforcement shall be of the type specified in the contract documents and shall conform to ASTM A185/A185M.	
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."

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 back-filled 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 5.2. 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 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 prehydration. 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.

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. 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