IN-LB Inch-Pound Units

SI International System of Units

Specifying Underground Shotcrete—Guide

Reported by ACI Committee 506

ACI PRC-506.5-22

American Concrete Institute
Always advancing

American Concrete Institute
Always advancing

First Printing
October 2022
ISBN: 978-1-64195-198-2

Specifying Underground Shotcrete—Guide

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at http://concrete.org/Publications/DocumentErrata.aspx. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided "as is" without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised the ACI Collection of Concrete Codes, Specifications, and Practices.

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

ACI PRC-506.5-22

Specifying Underground Shotcrete—Guide

Reported by ACI Committee 506

Simon Reny*, Chair

James A. Ragland, Secretary

Lars F. Balck
Louis-Samuel Bolduc
Chris D. Breeds*
Wern-Ping Nick Chen*
Scott R. Cumming*
William T. Drakeley Jr.*
Randle M. Emmrich
Charles S. Hanskat*
Marc Jolin*
Mark R. Lukkarilia
Axel G. Nitschke*
Ryan Oakes
Ryan E. Poole
Raymond C. Schallom*
William L. Snow Sr.
Jason P. South
Lawrence J. Totten*
Frank E. Townsend*
Marcus H. von der Hofen*
Ezgi Wilson
Peter T. Yen*
Lihe Zhang†

Consulting Members

Jean-François Dufour
Richard A. Kaden
Dudley R. Morgan*
H. Celik Ozyildirim
Harvey W. Parker‡
Philip T. Seabrook

*Subcommittee members who produced this report.
†Subcommittee Chair who produced this report.
‡Deceased.

Note: The Committee acknowledges B. Edgerton, J. Lindell, J. O'Donnel Sr., and F. Sherrill for their contributions to this report.

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.

CONTENTS

ACI PRC-506.5-22 supersedes ACI 506.5R-09(16) and was adopted and published in October 2022.

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 and restrictive 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 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.

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.

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. 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 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/yd^3 (kg/m^3) or fl oz/yd^3 (L/m^3) based on saturated surface-dry (SSD) aggregates (b) Fiber content of steel fiber or other fibers, in lb/yd^3 (kg/m^3)	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 hydrated 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	*Cement*	
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	*Supplementary cementitious 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 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	*Aggregate*	
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	*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 to heat and hydrate the shotcrete mixture.
4.5	*Admixtures*	
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	*Fibers*	
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/C116M 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.	
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 post-crack load-carrying capacity (Bernard 2013, 2019).
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.

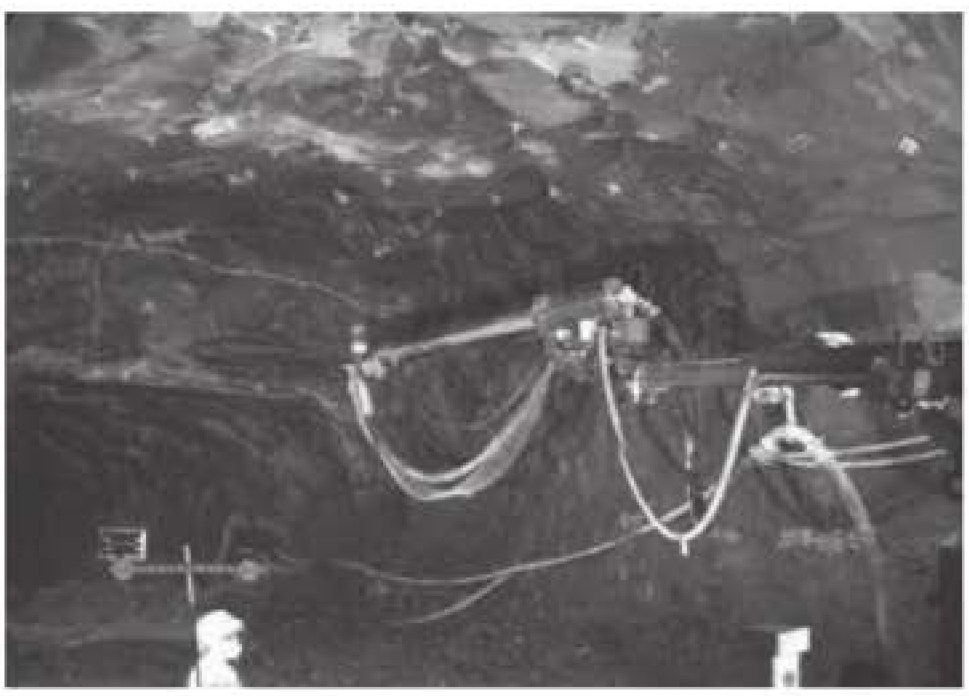

Fig. 5.2c—Tunnel with pattern bolting before shotcreting.

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 where 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 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.

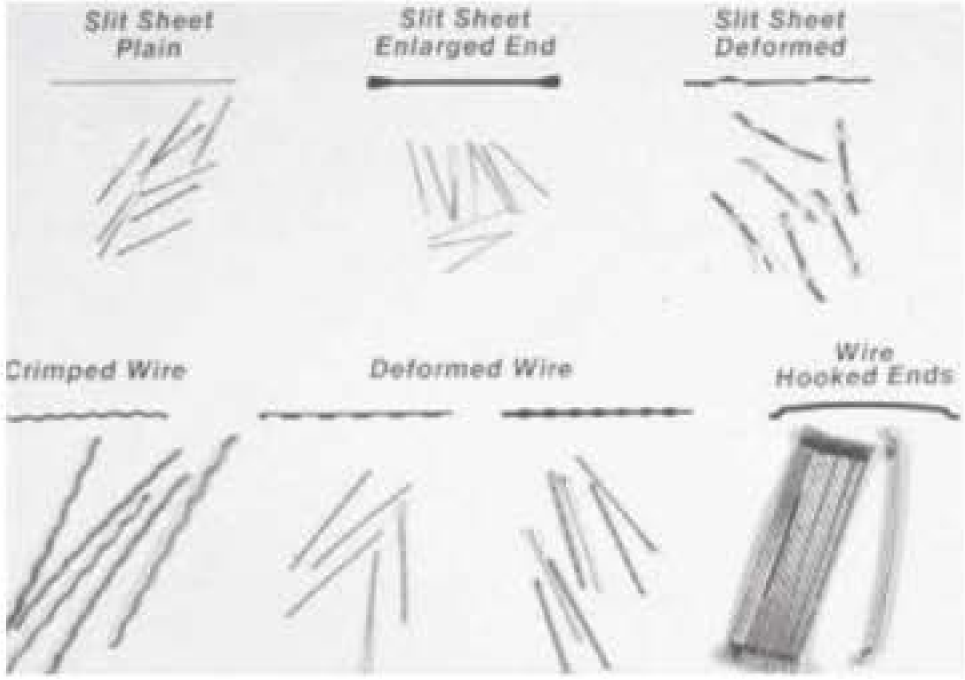

Fig. 5.4a—Close-up of steel fibers.

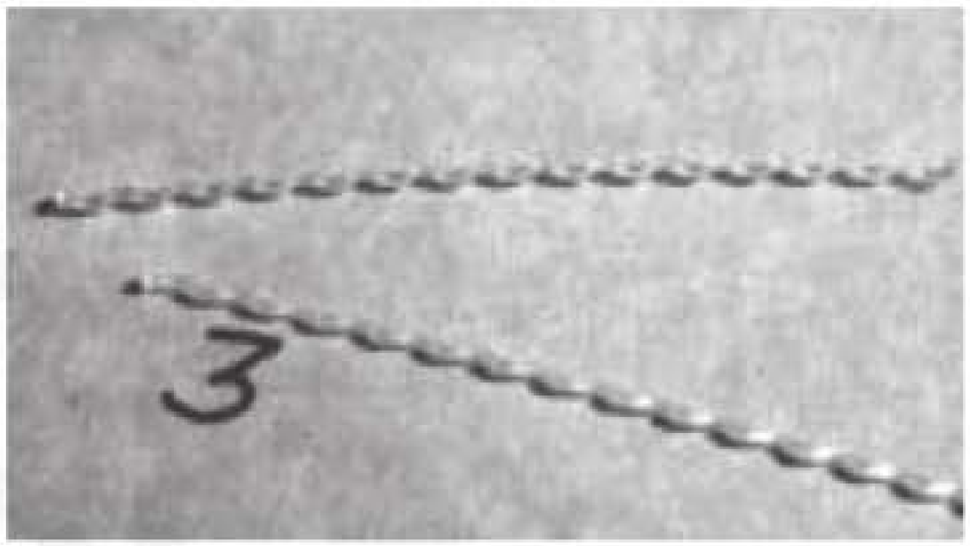

Fig. 5.4b—Close-up of macrosynthetic fibers.

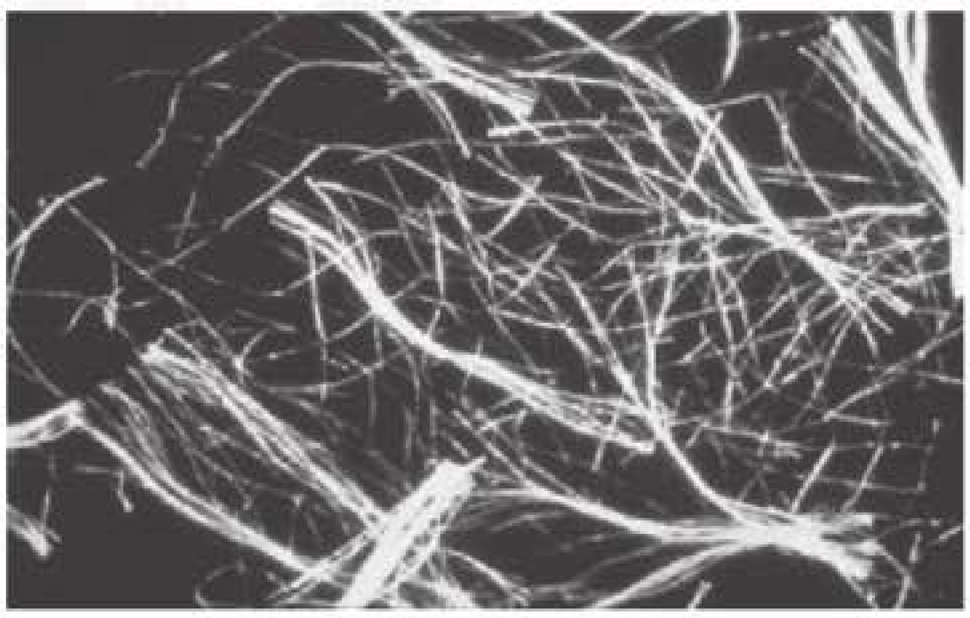

Fig. 5.4c—Close-up of microsynthetic fibers.

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/yd^3 (25 to 60 kg/m^3) (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/yd^3 (6 to 15 kg/m^3) 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/yd^3 (0.9 kg/m^3) for plastic shrinkage control, and 3 lb/yd^3 (1.8 kg/m^3) for explosive spalling mitigation. Fibers for explosive spalling protection should be 0.0013 in. (32 μm) 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.

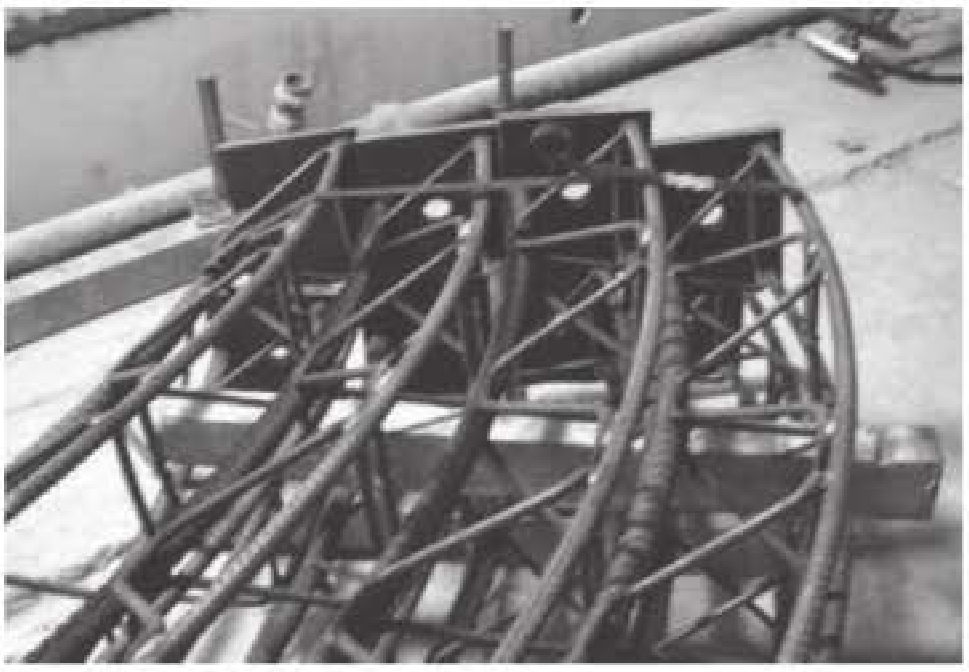

Fig. 5.5a—Close-up of a typical lattice girder.

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.

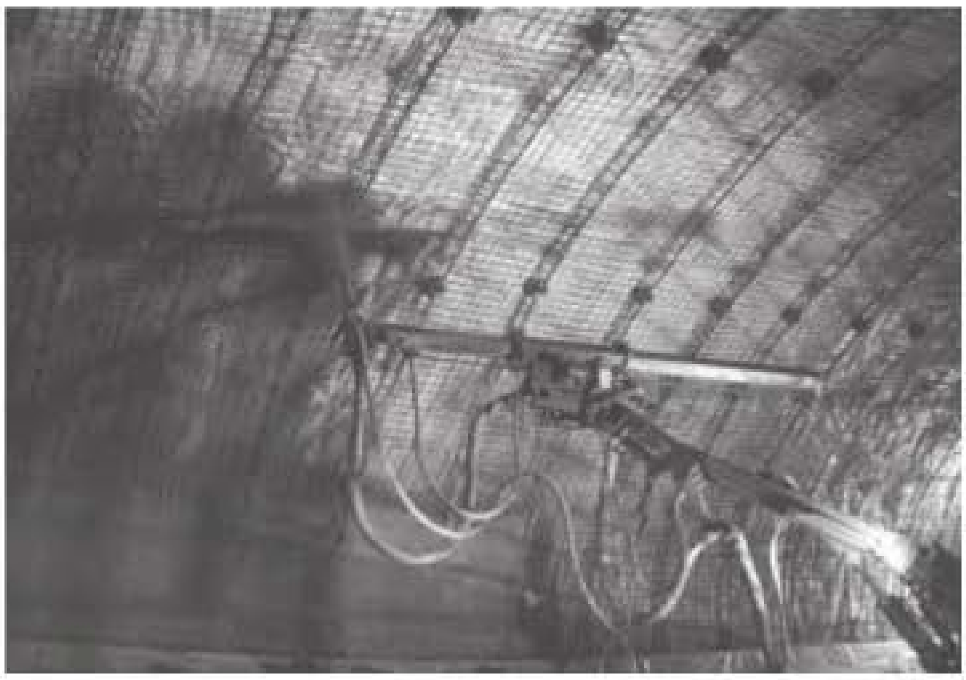

Fig. 5.5b—Typical lattice girder during shooting (robotic).

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.

Fig. 5.6—Steel sets with significant wood cribbing.

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	*Reinforcement*	
5.2.1	Welded wire reinforcement shall be of the type specified in the contract documents and shall conform to ASTM A185/A185M.	

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."

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-

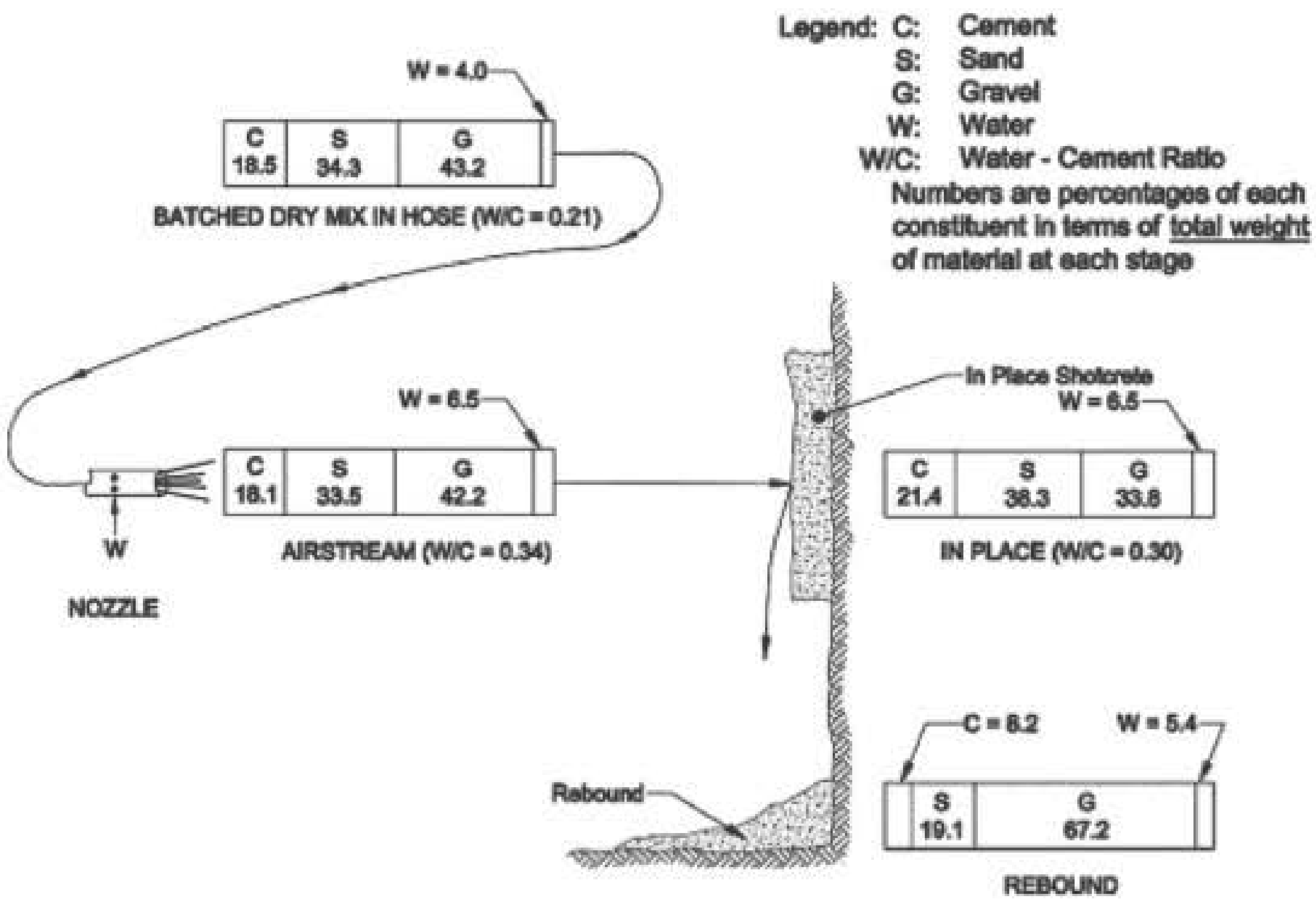

Fig. 7.3—Measurements of the percentage of various dry-mix components before and after shooting.

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/yd^3 [420 kg/m^3]) 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

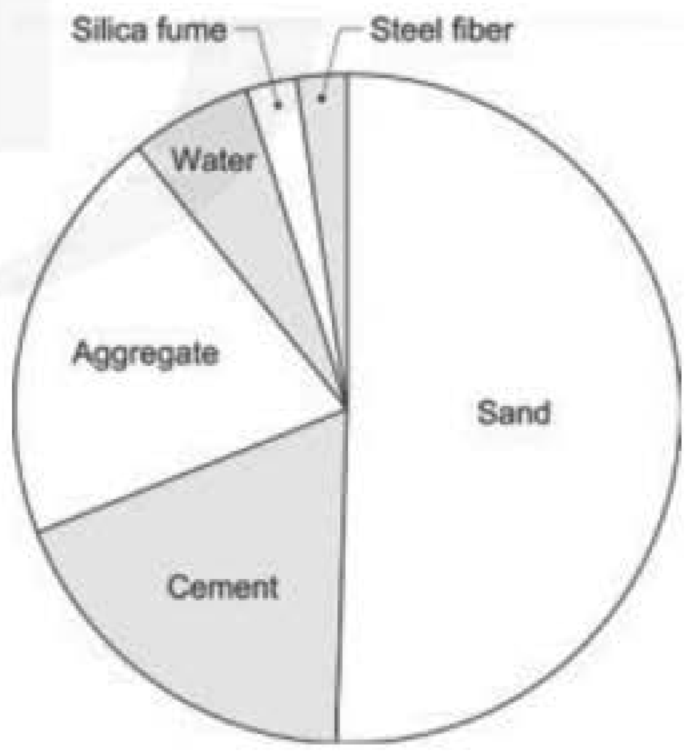

Fig. 7.4a—Typical mixture design for dry-mix underground shotcrete (percent by weight).

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	85	50

should be contacted for additional information regarding impact on ultimate strength and durability.

When powdered accelerating admixtures are used, pre-dampeners should not be used because premature setting may occur in the hoses (Jolin et al. 1997). The use of a hydromix nozzle is a good alternative to pre-dampening when powder accelerator is present in the shotcrete mixture. Advances in technology also have made it possible to inject metered accelerator directly into the water stream to the nozzle. This gives the contractor the ability to adjust the dosage of accelerator, depending on the ground conditions (and pump rate). This system eliminates the rapid set times in pre-dampened dry mixtures with powdered accelerators. The normal 45-minute rule for pre-dampened material works well with this system.

When frost resistance is necessary, an air void spacing factor lower than 0.012 in. (300 μm) may be obtained in dry-mix shotcrete if a liquid or powdered air-entraining admixture is used. The liquid air-entraining admixture is diluted in the water used for shooting at a dosage of approximately 1.3 to 2.6 fl oz/gal. (10 to 20 mL/L) of water. The powdered air-entraining admixture is prepackaged with the dry materials (cement, silica fume, and aggregates). The dosage may vary depending on the type of powdered air-entraining admixture (Beaupré et al. 1996).

Fiber reinforcement is often used for underground applications to reinforce the shotcrete. For dry-mix shotcrete, steel fiber is mostly used, but some types of synthetic fibers may also be used.

7.5—Wet-mix shotcrete

For wet-mix shotcrete, the modifications of the composition (increase in the cementitious materials proportion and reduction in the size and proportion of the coarse aggregate) are aimed at improving the application and pumpability of the shotcrete. Table 7.5 gives typical compositions of three shotcrete mixtures with a *w/cm* of 0.45. Figures 7.5a and

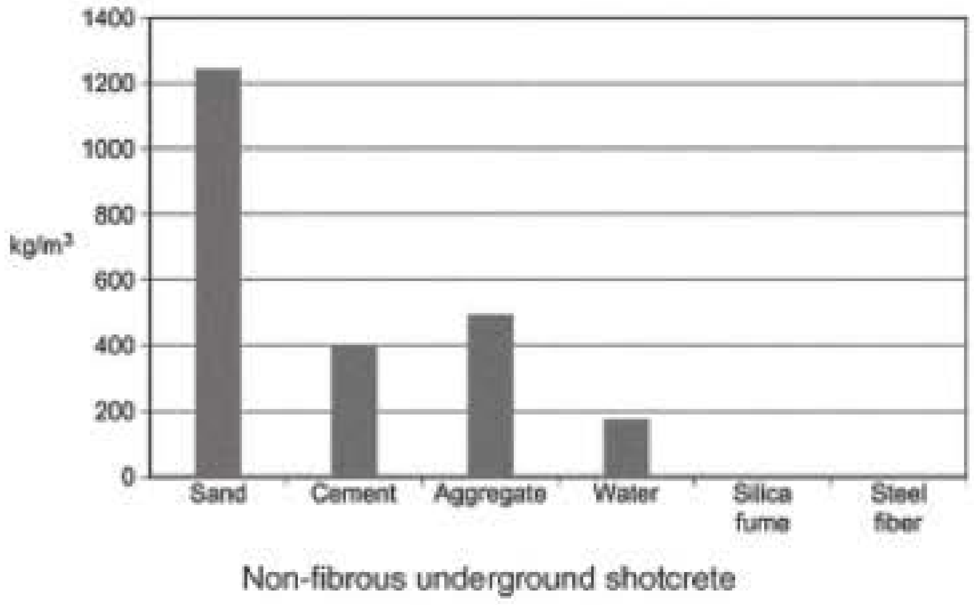

Fig. 7.5a—Typical wet-mix design for underground shotcrete (%).

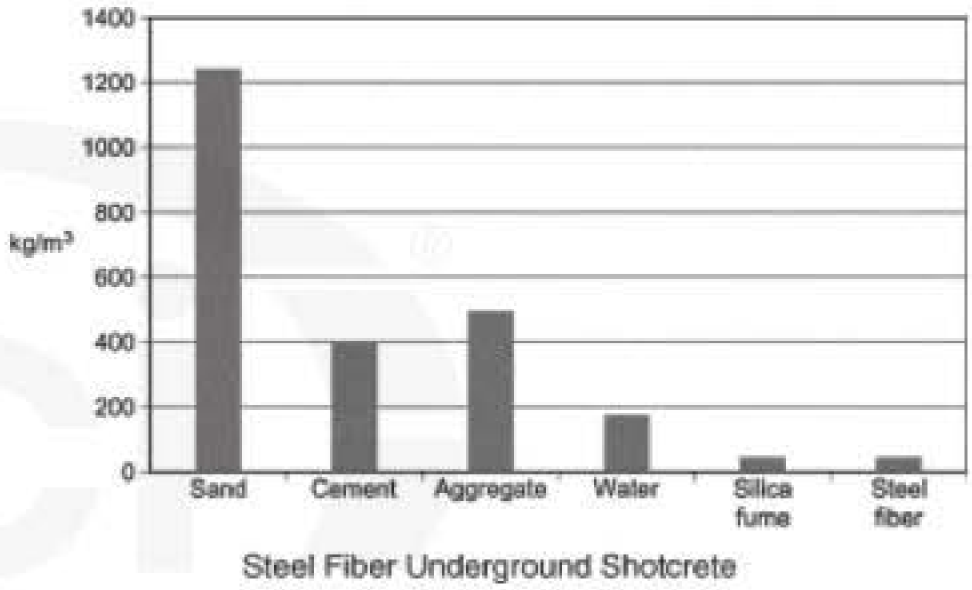

Fig. 7.5b—Typical wet-mix design for underground shotcrete with silica fume and steel fibers.

Table 7.5—Typical compositions of underground wet-mix shotcrete mixture proportions

	Wet-mix shotcrete (*w/cm* = 0.45) with entrained air		
Constituents	Ordinary shotcrete	With silica fume	With fibers and silica fume
Water	300 lb/yd³ (180 kg/m³)	300 lb/yd³ (180 kg/m³)	300 lb/yd³ (180 kg/m³)
Cement	675 lb/yd³ (400 kg/m³)	605 lb/yd³ (360 kg/m³)	605 lb/yd³ (360 kg/m³)
Silica fume	—	70 lb/yd³ (40 kg/m³)	70 lb/yd³ (40 kg/m³)
Sand	2100 lb/yd³ (1250 kg/m³)	2100 lb/yd³ (1250 kg/m³)	2100 lb/yd³ (1250 kg/m³)
Coarse aggregate (maximum 3/8 in. [9.5 mm])	840 lb/yd³ (500 kg/m³)	840 lb/yd³ (500 kg/m³)	800 lb/yd³ (475 kg/m³)
Steel fibers	—	—	85 lb/yd³ (50 kg/m³)
Air-entraining admixture*	8 fl oz/yd³ (0.3 L/m³)	8 fl oz/yd³ (0.3 L/m³)	13 fl oz/yd³ (0.5 L/m³)
Water-reducing admixture*	40 fl oz/yd³ (1.5 L/m³)	40 fl oz/yd³ (1.5 L/m³)	40 fl oz/yd³ (1.5 L/m³)
High-range water-reducing admixture*	—	26 fl oz/yd³ (1.0 L/m³)	40 fl oz/yd³ (1.5 L/m³)
Slump before pumping†	3 to 5 in. (75 to 125 mm)	3 to 5 in. (75 to 125 mm)	3 to 5 in. (75 to 125 mm)
Air content before pumping‡	7 to 10%	7 to 10%	7 to 10%

*Admixture dosages presented in this table are only for general information and depend on type of admixture and on characteristics desired in fresh shotcrete.

†Especially in mining, where handling and transportation of shotcrete occurs extensively before pumping and placement, slumps in the range of 6 to 10 in. (150 to 250 mm) may be specified. This approach, consistent with the contemporary European shotcrete culture, features greater slump retention and workability of the mixture, and is gaining popularity in the North American underground environment.

‡The process of shooting the wet-mix results in a reduction of air content. Air content of as-shot, in-place shotcrete is typically reduced by approximately half compared with air content before pumping.

7.5b illustrate these data graphically. The dosages of water-reducing admixtures, high-range water-reducing admixtures, or both, and air-entraining admixture should be adjusted by means of trial batches and field tests so that the desired slump and air content are obtained before pumping.

Similar to dry-mix shotcrete, the wet-mix technique also requires that aggregates be blended to conform to a smooth curve within the ACI No. 2 grading limits. Because the maximum *w/cm* is usually specified at approximately 0.45, the desired workability (slump of 3 to 5 in. [75 to 125 mm]) can only be obtained at a cementitious material content of approximately 675 lb/yd^3 (400 kg/m^3) or higher and with the aid of a high-range water-reducing admixture at an addition rate of approximately 0.5 to 1.0% by mass of cement. Mid-range water reducers and hydration-controlling admixtures have also been used to reach the same slump requirements. For higher slumps, high-range water reducers have been added at the job site before shooting.

Admixtures, such as air-entraining admixtures, are available that, in the case of poor pumpability of a wet-mix shotcrete due to deleterious characteristics of available aggregates, may be included to enhance the pumpability aspects.

For underground applications, liquid accelerator admixture is mainly used for overhead shooting to increase the buildup thickness and to accelerate the early strength development. The accelerator admixture is added at the nozzle and the nozzleman can control the quantity with a valve, depending on the placing conditions. Calibrated metering pumps should be used to prevent over- or under-acceleration of the concrete that is placed. Accelerator is used in both vertical and overhead applications to achieve the required thickness. Vertical applications generally require less accelerator than overhead applications for the same thickness. Many underground projects are using higher slump for pumpability and accelerator to make the shotcrete placeable.

In the case of wet-mix shotcrete, entrained air provides good freezing-and-thawing resistance and facilitates the pumping process (Beaupré 1994). The air content before pumping should vary from 7 to 10%. The air content of the in-place shotcrete would be approximately 3 to 5%, depending on the pumping pressure and the length and configuration of the hoses. Note that high-volume air entrainment (7 to 10%) should not be used in shotcrete that is dropped down supply pipes. The air can be knocked out during the drop and impact in the receiving boot or kettle, which adversely affects workability (slump). If air entrainment is required in such a case, it should be added in a re-mixer unit underground after the shotcrete has been dropped down the supply pipe. If the 4 to 5% displacement of air is not achieved by the proper compaction upon impact to the receiving surface, low strength and durability will result. High air content in the concrete will also change the yield per cubic meter. Air

Table 7.6—Example guide specification for mixture proportioning

Section/ Part/Article	Recommended specification language	Notes to the Specifier
7.1	*Shotcrete mixture proportioning*	
7.1.1	Proportion shotcrete mixtures to meet the performance requirements detailed in the project specifications.	The performance requirements shown in Chapter 8 should be compatible with the ability to proportion mixtures to comply with them.
7.1.2	Make allowances in shotcrete mixture proportioning for the following criteria: (a) Shotcrete application process (wet-mix or dry-mix shotcrete) (b) Shooting orientation (overhead or vertical surfaces) (c) Changes in in-place mixture proportions as a result of rebound (d) Changes in required time of setting of shotcrete under different tunneling/mining conditions (for example, groundwater inflow) (e) Changes in groundwater conditions in substrate rock	The shooting application process should be addressed for both the owner and the contractor. Shooting orientation needs to be handled carefully. There are times when conditions create a situation that must be handled by different means outside the description in the contract documents. Vertical surfaces are often shotcreted first before carrying out overhead spraying. This practice provides an opportunity to troubleshoot the mixture, thereby increasing safety and minimizing overspray. Using hydration control admixtures in the concrete mixture gives the contractor the necessary time for placement in case a problem arises. The ability to adjust the proportion of accelerator in the mixture gives the contractor the range of set time in case the ground conditions change. (Note: the range of accelerator dosage is usually set during the pretesting phase of the project.)
7.1.3	Provide an easily identifiable code or number on all batch documentation, in-place shotcrete, and test panels to identify the use of different shotcrete mixtures.	The test panel number and test cores should be correlated to shotcrete mixture used, nozzleman, time, date, and physical location of shotcrete placement in the tunnel section (that is, by station number). This relationship is important if panel or core test results indicate below-specified shotcrete strength.
7.1.4	Shotcrete accelerator dosage shall not exceed maximum values provided by the supplier respectively as evaluated during preconstruction testing. If accelerator is used for final lining applications, the contractor shall provide evidence that durability is not negatively impacted.	Refer to the extended discussion of accelerators in Section 4.1.

helps in the pumping process but should not be relied upon as a pumping aid. The use of water reducers will generally aid pumping.

Steel or macrosynthetic fibers are often used as reinforcement when shotcrete is placed underground. The addition of fibers to the mixture increases the load-carrying capacity of the shotcrete after cracking. Such characteristics are generally important in underground support.

More information concerning the properties and use of various additives and admixtures, such as silica fume and accelerating admixtures, can be found in Chapter 4.

7.6—Recommended specifications

Recommended specifications for mixture proportioning are provided in Table 7.6. 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 8—PERFORMANCE REQUIREMENTS

8.1—General

Performance requirements for underground conditions are a function of the application. Hence, when specifications are developed, one should keep in mind the requirements for the application concerned. For example, whereas final lining shotcrete for civil tunneling projects emphasizes strength and durability, mining projects and shotcrete for initial support typically emphasize early-age strength gain. Generally accepted values for performance requirements for high-quality shotcrete are presented in Table 8.1. The engineer should avoid over-specifying requirements that are not necessary but should include the essential requirements.

8.2—Water-cementitious materials ratio

The water-cementitious materials ratio (*w/cm*) should be as low as possible, consistent with the application and tunnel conditions, to achieve high-strength performance and provide durability. Practical limitations exist, however, and a maximum ratio of 0.45 is usually specified.

This specification is difficult to verify for dry-mix shotcrete unless special measurements are made on the fresh shotcrete after shooting. Instead of specifying a *w/cm* for dry-mix shotcrete, a minimum compressive strength and a maximum volume of permeable voids are often specified.

8.3—Air content

Entrained air content is not normally specified for underground support shotcrete unless freezing and thawing of the shotcrete (final) lining is expected. In the wet-mix process, the initial air content (at the pump) should be sufficiently high (7 to 10%) to provide an adequate spacing factor for the air voids after compaction has occurred during shooting, producing an in-place air content of between 3 and 5%.

Table 8.1—Typical shotcrete performance requirements

Shotcrete properties	Test method	Age	Wet-mix shotcrete specified limits	Dry-mix shotcrete specified limits
Maximum *w/cm*	—	—	0.40 to 0.45	—
Air content—as shot[*†‡], %	ASTM C231/C231M	—	4 ± 1	—
Air content—immediately before the pump[†§], %		—	7 to 10	—
Slump at discharge into pump[†‖], in. (mm)	ASTM C143/C143M	—	3 ± 1 (80 ± 30)	—
Maximum spacing factor—as shot, in. (μm)	ASTM C457/C457M	—	0.012 (300)	0.012 (300)
Maximum boiled absorption, %	ASTM C642	7 days	8	8
Maximum volume of permeable voids, %	ASTM C642	7 days	17	17
Minimum compressive strength, psi (MPa)	ASTM C1604/1604M	8 hours 1 day 3 days 7 days 28 days	800 (5.5) 1200 (8) 2200 (15) 4350 (30) 5800 (40)	800 (5.5) 1200 (8) 2200 (15) 4350 (30) 5800 (40)
Minimum flexural strength[#], psi (MPa)	ASTM C1609/C1609M or ASTM C78/C78M	7 days	600 to 650 (4.0 to 4.5)	600 to 650 (4.0 to 4.5)
Minimum flexural toughness for a 40 mm deflection[#], Joules	ASTM C1550	7 days	280	280
Minimum toughness performance level	Morgan et al. (1995)[**]	7 days	III	III

[*]Air content determined as shot into an ASTM C231/C231M air pressure meter base or use fresh shotcrete recovered from in-place or a test panel.

[†]Requirements for wet-mix shotcrete only.

[‡]High air content results in lower concrete yields, durable concrete, and lower strengths.

[§]These values do not reflect the air content of hardened shotcrete.

[‖]Generally, high air content is preferable because it gives higher slump and, hence, better pumpability.

[#]Only specified if fibers are added to shotcrete mixture. Either flexural strength and toughness performance level or minimum toughness energy should be specified.

[**]Toughness testing only required for fiber-reinforced shotcrete that requires post-crack load capacity. Toughness Performance Level III requires a minimum post-crack flexural strength of 50% of the modulus of rupture of the shotcrete at a deflection of the test specimen of 1/600 of the test span, and a minimum post-crack flexural strength of 30% of the modulus of rupture of the shotcrete at a deflection of the test specimen of 1/150

Testing can be made on the pumped concrete according to ASTM C231/C231M. For shotcrete, the air content can be determined either by shooting directly into the base of an ASTM C231/C231M air pressure meter or by removing applied shotcrete from a test panel or in-place and reconsolidating it in the air pressure meter base. With accelerated shotcrete, the former method should be used. If the application of shotcrete does not result in a reduction of 4 to 5% air during pumping and shooting compaction, it will result in lower strengths and less-durable concrete.

In the dry-mix process, although the mixing time between the addition of water and other materials is short, an adequate air-void network can be created if the air-entraining admixture is first mixed (at high dosage) with the water used for addition at the nozzle. Alternatively, a dry, powdered air-entraining admixture can be preblended with the dry materials. If required, the spacing factor and air content should be evaluated on hardened specimens using the ASTM C457/C457M procedure. Again, the nozzle velocity will determine how much air will be displaced during compaction of the material placed. However, results from the ASTM C457/C457M procedure may take several weeks and it may thus apply to shotcrete in-place weeks earlier. If using ASTM C457/C457M, it is recommended to qualify the air content in preconstruction testing rather than in production testing.

8.4—Slump

The slump requirement is applicable only to concrete shot using the wet-mix process. Slump should be measured at the pump to monitor the relative consistency from batch to batch. The maximum slump is a function of: 1) the distance wet-mix shotcrete has to be pumped; 2) temperature; 3) elevation; 4) retention time; and 5) other shooting conditions, but will normally be between 2 and 4 in. (50 and 100 mm). As air content is lost upon compaction on the shooting surface, the slump is reduced. This slump-reduction effect is very beneficial to the shotcrete application process, reducing the amount of shotcrete sagging, sloughing, and fallout. Either too low or too high slump will lead to pumping and application problems, both negatively impacting the shotcreting process and subsequently the shotcrete quality. The contractor should only attempt to pump shotcrete with a slump (measured at the point of discharge to the pump) between 2 and 4 in. (50 and 100 mm).

8.5—Boiled absorption and permeable voids

The absorption test, a procedure described by ASTM C642 to assess the degree to which the pores within hardened concrete are interconnected, determines the amount of water that shotcrete can absorb and thereby evaluates the porosity of the shotcrete. Both boiled absorption and permeable void data can be used as indicators of shotcrete quality because a correlation exists between the two parameters.

Several factors can influence boiled absorption and the volume of permeable voids in shotcrete. The use of accelerators can increase boiled absorption and permeable voids in hardened shotcrete. The type and quality of curing can also be a factor. Improper shooting techniques, such as shooting from a distance too great from the rock surface or improper shooting angles, can increase values of boiled absorption and volume of permeable voids.

The absorption rate for the aggregates used in the shotcrete mixture also affects boiled absorption and volume of permeable voids. Aggregates with higher absorption show higher test results of absorption and volume of permeable voids. If high-absorption aggregates are used in the shotcrete, preconstruction samples can be tested for boiled absorption, results can be used as a reference based on which boiled absorption for shotcrete can be compared, and shotcrete placement quality can be evaluated.

Boiled absorption and permeable void requirements should be specified when shotcrete mixtures are designed to be durable, such as those for final tunnel linings and permanent openings in underground mining.

8.6—Compressive strength

The required minimum compressive strength at a given age is dependent upon how the shotcrete lining is required to perform. When immediate support is required, a specified compressive strength at 8 hours or earlier may be critical. On the other hand, if the lining does not require any specific early strength, only a 7- or 28-day compressive strength may be specified. Specifications can be made for 8 hours; 1, 3, and 7 days; and 28 days if the strength gain characteristics are critical (refer to Section 8.7). Eight hours is generally the earliest time specimens can be obtained without damage for conducting ASTM C1604/C1604M testing. An average 28-day compressive strength is generally specified as greater than 4350 psi (30 MPa). For some applications, such as a permanent tunnel lining, an average 28-day compressive strength of 6000 psi (40 MPa) or more may be specified. However, the shotcrete strength should not be over-specified compared to the strength required for structural purposes.

8.7—Flexural strength and toughness

Flexural strengths are not normally specified unless fiber-reinforced shotcrete is specified. The flexural strength is usually specified using the flexural toughness test, ASTM C1609/C1609M, but the ASTM C78/C78M test method may be used to determine the ultimate flexural strength only. Although no general agreement exists regarding the best criterion to be adopted for toughness parameters (such as ASTM residual strength, toughness performance level, or Japan Society of Civil Engineers [JSCE] toughness), general guidance can be found in papers by Morgan et al. (1995) and the Norwegian Concrete Association (2003). Other values, such as flexural toughness (in Joules), can also be specified according to the round panel test, ASTM C1550 (Papworth 2002; Clements 2003; Bernard 2004; Grimstad et al. 2002) and ACI 506.1R.

8.8—Early-age strength

Early-age strength development is a requirement frequently imposed on shotcrete used for ground support. Early-age strength testing is conducted to provide strength develop-

ment with time. Early-age tests at 2, 4, 6, 8, and 12 hours, or at other ages, are possible using large-scale pull plate tests (Dufour et al. 2002), compression testing of the ends of beams (Morgan et al. 1999b), or the stud driving method. These are followed by 24-hour, 72-hour, 7-day, and 28-day strength tests described in ASTM C42/C42M. Coring, at an early age, can potentially cause damage to the cores (refer to ASTM C42/C42M and C1604/C1604M). Alternatively, an index of strength and strength gain can be obtained, even immediately after shooting, from special penetration tests (Bernard 2005). Strength-penetration tests are used to crudely approximate the in-place strength (ACI 506.4R).

Some accelerating admixtures may facilitate high early-strength development but reduce the 28-day strength. In addition, the rate of the strength development curve provides a means of assessing marginal shotcrete core strengths during the construction phase of the project, as described in ASTM C1074.

8.9—Other tests

Occasionally, shotcrete used for ground support requires other properties that may affect durability, resistance to freezing and thawing, or permeability where it functions as a sealing system. Tests for absorption, drying shrinkage, resistance to freezing and thawing, permeability, or bond may be required. Specimens for such testing may be obtained from shotcrete test panels or from in-place shotcrete by extracting cores or sawing cubes and beams (ASTM C42/C42M and C1604/C1604M).

8.10—Bond strength

Where shotcrete to a high-quality rock interface has been cored and tested in direct tension, typical bond strengths of 150 to 200 psi (1 to 1.5 MPa) are common (CSA A23.2-6B). Bond measurements show a substantial degree of variability unless special provisions are taken during preparation and sampling. Core samples should be visually inspected to determine inclination of the interface relative to the core axis. If the angle of the interface is more than a few degrees from a right angle, the results of tension or indirect shear loading can measurably distort the estimate of bond properties. At the completion of such testing, the failure surface of the cored interface should be inspected. Often, failure of the specimen does not occur at the plane of the interface, but at a small angle through solid rock and into the shotcrete. Bond failure at the interface between rock and shotcrete is unusual unless some latent conditions detrimental to bond exist.

If the interface between the rock and shotcrete is rough, irregular, or undulating, the measured bond properties will be subject to variability, and the size of the specimen will influence the results. The nature of shotcrete bond is not completely understood. The bond can, in part, be attributed to mechanical or physical keying and friction, and may, in certain cases, be enhanced chemically where rock and cement paste react after shotcrete placement. Taken as a whole, these factors, when considered over the profile of a tunnel, will produce a wide range of bond strengths. Unless a large sampling program is used to statistically determine the range and variability of bond properties, limited test data should be viewed conservatively should the engineer attempt to factor such properties into ground support design.

Where a limited number of core specimens have been extracted from a shotcrete lining, the bond strength test results should only be used to confirm that the required minimum bonding has been achieved. A nominal bond can, and should, be achieved between shotcrete and tunnel or opening profile using standard shotcrete practice. Reduced shotcrete bond can occur due to numerous reasons, which will be discussed in Chapter 16. If QC inspection and testing results show that the required bonding has not been achieved, this condition may be considered deficient shotcrete and, in certain projects, be cause for the issuance of a nonconformance.

8.11—Fire-induced explosive spalling protection

Polypropylene microfibers have been shown to prevent explosive spalling of shotcrete when subjected to intense, hydrocarbon-fueled fires (Tatnall 2002). Localized mining-induced seismic events can cause stress conditions that result in explosive spalling (ACI 506.1R).

8.12—Recommended specifications

Recommended specifications for mixture proportioning are provided in Table 8.12. 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 8.12—Example guide specification for performance requirements

Section/Part/ Article	Recommended specification language	Notes to the Specifier
8.1	Performance requirements: Proportion the shotcrete mixture to meet the performance requirements shown in Table 8.1	The specifier should adjust the typical values shown in Table 8.1 to meet the specific requirements for the project at hand.

CHAPTER 9—QUALITY ASSURANCE AND QUALITY CONTROL

9.1—General

The contractor placing the shotcrete should employ a QC program. On large underground projects, the project specifications may dictate that the contractor provides a QC function that includes inspection and testing. Under these circumstances, the contractor should actively and effectively participate in the overall project QA/QC program. If subcontractors or material suppliers are engaged in the production or supply of shotcrete, they should also bear their share of responsibility for the quality of the shotcrete. Contractors operating their own shotcrete production facilities should assume direct responsibility for QC activities.

This chapter provides an overview of the QA and QC plans, procedures, and activities associated with the installation of ground support systems in mining, tunneling, or underground construction projects. The overview is confined to typical use of shotcrete in combination with rock bolts,

Table 9.2—Example guide specification for quality assurance and control

Section/ Part/ Article	Recommended specification language	Notes to the Specifier
9.1	General: The owner shall implement a QA program for the work. Such a program shall include, but not be limited to, these specifications.	The owner is typically responsible for quality planning and overall management that includes the selection of competent organizations and individuals and the establishment of a QA system that will meet the owner's objectives.
9.1.1	Review of contractor submittals.	Refer to Chapter 3. The implementation of established controls should be described in a quality program that documents the procedures and instructions to be carried out. Established controls may include supplier evaluation and selection, procurement documents, receiving inspection, storage and handling of materials, materials qualification, and records.
9.1.2	Review and approve contractor's proposed materials, supply, equipment, and crew. In particular, all shotcrete nozzlemen proposed for use on the project shall be evaluated in the preconstruction testing program—only nozzlemen approved in writing by the owner shall be used on the project. The owner shall also reserve the right to either remove the nozzleman from the project or require re-training, and reapproval, if nozzleman repeatedly produces deficient work or results.	Refer to Chapter 10. The owner should also reserve the right to access all applicable records and documents, such as: contractual documents, quality procedures and instructions, personnel qualifications records, design drawings and calculations, specifications, procurement documents, material qualification records, field sketches, shop and working drawings, change orders, technical reports, photographs, inspection and test records, nonconformance reports, shotcrete mixture proportions, as-built drawings, contractor's logs, survey reports, and check reports.
9.1.3	Examine and approve all areas prepared for shotcreting, including preparation of rock, installation of water control measures, anchors, reinforcement, waterproofing membranes, and devices to control shotcrete thickness, before application of any shotcrete.	Refer to Chapter 11 for details on tunnel inspections before shotcreting.
9.1.4	Provide inspectors to monitor shotcrete installation, with the authority to require removal and replacement of nonconforming shotcrete while still fresh.	Refer to Chapter 11 for details on inspector qualifications and responsibilities.
9.1.5	Regularly monitor the results of the contractor's quality control testing.	
9.1.6	Implement a program for evaluating in-place shotcrete for acceptance or rejection, where construction test results indicate shotcrete not conforming to the project specifications.	Refer to Chapter 11.
9.1.7	Implement a program of remedial work, where QA program results indicate remediation is necessary.	
9.2	Quality control: The contractor shall implement a QC program for the shotcrete work to ensure compliance with the contract documents. Such a program shall include, but not be limited to, these specifications.	The provisions of a project QA/QC plan are usually implemented using a framework of project procedures and drawings. These provide the project participants with the necessary and sufficient information for the contractor to satisfy the QA/QC requirements established by the design.
9.2.1	Maintenance of test records for all QC operations.	Each organization should be responsible for the technical content and accuracy of their records or documents that furnish evidence of quality of materials, equipment, or activities. Records or documents should be signed, or otherwise authenticated, and dated by a responsible individual from the organization initiating the record(s). An index should be established and maintained to identify and retrieve a specific record by the designated individual or organization. The project QA/QC organization should retain these records typically produced during shotcrete operations: batch time delivery, discharge time, and batch proportions used; admixture quantities used; time and temperature of batching; placement location; special precautions for hot or cold weather conditions; and the identity of the qualified nozzlemen who performed the work.

lattice girders, and steel sets when used as composite ground-support systems, and it focuses on the shotcrete application.

9.2—Recommended specifications

Recommended specifications for quality assurance and control are provided in Table 9.2. 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 10—PRECONSTRUCTION TRIALS AND TESTING

10.1—General

Preconstruction testing enables the owner to evaluate conformance of the proposed materials, shotcrete mixture, equipment, and crew to the specification.

In certain special cases (that is, use of prototypes, final lining, installation on waterproofing membranes, embedment of reinforcement/lattice girder), the owner/engineer may require the contractor to demonstrate certain aspects of the shotcrete installation by in-place testing or by constructing a mockup. This may require use of part of the tunnel structure or an alternative surface or subsurface facility. An example of this type of testing is a demonstration of ground support installation that includes rock bolts, lattice girders, and shotcrete in concert with the excavation process. Prototype testing can also include both the excavation of test tunnels and ground support installation. To evaluate the performance of the ground support including shotcrete, these test tunnel sections may use geotechnical instrumentation, monitoring, and numerous sampling and testing methods that require in-place destructive and nondestructive tests.

Where specific excavation tolerance or finishes are required, shotcrete application and finishing procedures should also be demonstrated. If special equipment is to be used, such as batching, material handling, or shotcrete placement equipment, the contractor should demonstrate the supporting logistics, materials-handling methods, and procedures. Figures 10.1a and 10.1b illustrate shotcreting a test panel, Fig. 10.1c shows underground test panels, and Fig. 10.1d shows shotcreting of overhead test panels.

10.2—Recommended specifications

Recommended specifications for preconstruction testing are provided in Table 10.2. The information is provided in a guide specification format: the left column provides the

Fig. 10.1a—Shotcreting a test panel.

Fig. 10.1b—Shotcreting a test panel with a robotic nozzle.

Fig. 10.1c—Underground test panels.

Fig. 10.1d—Shotcreting overhead panels.

Table 10.2—Example guide specification for preconstruction testing

Section/ Part/ Article	Recommended specification language	Notes to the Specifier
10.1	Materials qualification	Refer to Chapter 4.
10.1.1	Materials, equipment, personnel, and procedures used in preconstruction testing shall be those that will be used for the work.	On large or time-sensitive projects, consider specifying and prequalifying alternative sources of shotcrete constituents to minimize risk of project delays. If normal sources are disrupted, alternative materials that have been prequalified during preconstruction can be substituted. The potential disruption due to the lack of availability of these materials is therefore minimized.
10.1.2	Materials used in preconstruction testing shall be stored and handled as specified for the work.	Refer to Chapter 6.
10.2	Nozzleman prequalification	The application of shotcrete cannot tolerate inexperience or marginal workmanship. This is particularly true where early and effective shotcrete application is essential to providing a safe working environment.
10.2.1	The preconstruction trial shall be used to prequalify the nozzlemen proposed for use on the project, in accordance with ACI CP-60. Nozzlemen may also be certified by the American Concrete Institute as outlined in ACI CP-60 as a prerequisite to prequalification. Nozzlemen who have not been prequalified shall not be permitted to apply shotcrete for the work.	A shotcrete demonstration, using test panels, provides a simple and direct means of evaluating workmanship, strength, uniformity, and other applicable properties as required by project specification. In the case of robotic applications, the nozzleman should also be required to shoot panels by hand.
10.2.2	If a prequalification test panel is rejected, the nozzleman shall be permitted to shoot a second test panel. If the second test panel is also rejected, the nozzleman shall not be permitted to shoot for the work until successful completion of an appropriate training program and demonstrated ability to shoot suitable quality test panels.	Acceptance of nozzlemen is usually contingent upon a nozzleman's successful placement of shotcrete overhead on a test panel while meeting all test requirements. Nozzlemen are required to shoot a vertical panel before they can shoot an overhead panel.
10.2.3	Each nozzleman shall shoot two preconstruction test panels for each shooting orientation in the work. The first test panel shall contain no reinforcements (with the exception of fiber reinforcement) to allow for extraction of shotcrete specimens for compliance testing. The second test panel shall contain a shotcrete anchor plate and/or any other reinforcing as detailed in the contract documents.	The test panel configuration typically used to qualify both materials and acceptable equipment and personnel is described in ASTM C1140/C1140M.
10.2.4	The test panels shall be produced in accordance with the requirements of ASTM C1140/C1140M except that they shall have minimum dimensions (at the top of the form) of 2 ft x 2 ft x 6 in. (600 x 600 x 150 mm deep). Test panels shall be made from wood, sealed plywood, or steel, and shall have 45-degree sloped-edge forms to permit escape of rebound and facilitate removal of the shotcrete panel. Test panels will weigh over 300 lb (136 kg) and will require lifting assistance.	This recommended size of test panel allows at least nine cores with a minimum diameter of 3 in. (75 mm) and three ASTM C1609/C1609M flexural strength and toughness beams to be extracted. If more than 6 in. (150 mm) of shotcrete is applied to the panel, cores with acceptable length-diameter (*L/D*) aspect ratios can be removed as described by ASTM C1604/1604M. A nominal 3 in. (75 mm) core diameter should be used. Where an *L/D* is less than 2 but greater than 1, an adjustment to the core compressive strength should be made as described in ASTM C1604/C1604M.
10.2.5	Field cure preconstruction test panels in the wood forms in the same manner as the proposed shotcrete work (keep out of sun, keep from freezing, keep damp) for a minimum of 2 days and not more than 3 days before transport to the test laboratory. Transport test panels in their forms, taking care not to crack or damage the shotcrete during transportation.	
10.2.6	At the laboratory, remove the test panels from their forms and place in a moist room that is maintained at a temperature of 75 ± 2°F (23 ± 1°C). Maintain test specimens in a moist state in the moist room until the time of testing.	
10.2.7	At appropriate test ages, extract test specimens from the panels using diamond sawing, coring, or both, and test them for the specified performance parameters.	Refer to Chapter 8 and ACI 506.1R. Visual examination of cores or cut surfaces of beams provides a simple and direct means of determining the uniformity of shotcrete. Note that this is a qualitative, and not quantitative, evaluation.
10.2.8	Extract at least one 3 in. (75 mm) diameter core from the location of a rock bolt in the second test panel to check the adequacy of consolidation of shotcrete around the spider and anchor. Two cores shall be extracted at locations of reinforcing steel (if any).	Preconstruction testing of rock bolts based on rock bolt installation and pullout testing is considered standard on most projects.

Table 10.2, cont.—Example guide specification for preconstruction testing

10.2.9	Specimens for compressive strength testing to ASTM C1604/1604M and for boiled absorption and volume of permeable voids testing to ASTM C642 shall be 3 in. (75 mm) diameter cores at least 4 in. (100 mm) long, or 4 in. (100 mm) cubes cut from the broken ends of flexural prisms.	If cube specimens are required by project specification, then the correlation factor of 0.85 should be applied. Core or cube testing becomes problematic when early strength tests are required. This requirement is usually imposed when higher shotcrete strengths are required. Typically, 8-hour strengths of 1200 psi (8 MPa) are verified by test panel specimens. This means that test facilities, equipment, personnel, logistics, and handling must be capable of expediting such testing. Cores can typically be removed after 6 hours and tested at 8 hours. Cubes can be acquired as early as 4 hours if coring is impractical or disturbs the shotcrete. Whether the indicated timelines can be met is highly dependent on the shotcrete mixture proportion, including accelerator type and dosage, and on shotcrete and substrate temperatures.
10.2.10	Specimens for flexural strength and toughness testing to ASTM C1609/C1609M shall be 4 x 4 x 14 in. (100 x 100 x 350 mm) prisms. Specimens for flexural toughness testing to ASTM C1550 shall be 32 in. (800 mm) diameter by 3 in. (75 mm) thick.	Fiber-reinforced shotcrete is normally tested in accordance with ASTM C1609/C1609M. If post-cracking properties were specified in the ground support design, demonstrating that the fiber reinforcement system is performing as required is important. Toughness values are typically used but should be compatible with the project service conditions.
10.3	Mixture proportioning qualification	Refer to Chapter 7.
10.3.1	Mixture used in preconstruction testing shall be the same proposed for production work.	Refer to Chapter 12.
10.3.2	If the preconstruction test specimens fail to meet the performance requirements, make the necessary adjustments in shotcrete materials, mixture proportions, or application procedures, and reshoot test panels. No shotcrete work shall commence until the preconstruction performance testing requirements have been met.	
10.4	*Final lining qualification*	
10.4.1	Shotcrete final lining installation and finishing procedures shall be demonstrated to the satisfaction of the owner on a large-scale mockup prior to the start of construction. The mock-up shall simulate the in-place conditions as realistic as possible and shall include reinforcement, lattice girders, and waterproofing membranes, as applicable. In addition, finishing procedures and tolerance, as specified by A/E, shall be tested.	

recommended specification language, and the right column provides notes to the specifier.

CHAPTER 11—CONSTRUCTION ACCEPTANCE INSPECTION

11.1—General

Construction acceptance inspection is key for an effective, efficient, and safe project, especially in the case of ground support or final lining installation and shotcrete application. The term "inspection," as used in this chapter, includes not only visual observations and field measurements, but also laboratory testing on samples taken during production work as well as assembly and evaluation of test data. The ability of the inspector to observe and recognize potential problems is essential.

On complex shotcrete projects, qualified or certified shotcrete inspectors with relevant underground experience should be engaged for the project (ACI CPP 661.1).

11.2—Acceptance inspection

The owner's project engineer should evaluate the need to conduct preconstruction testing and determine the overall scope of associated testing requirements. Sampling and testing of shotcrete at established intervals during construction is usually required. Some properties need to be monitored on a shift-by-shift basis, and others on a daily, weekly, or monthly basis. Where ground support installation becomes critical during the excavation cycle, shotcrete placement may become subject to inspection and testing on a shift-by-shift basis. Inspection requirements should be commensurate with complexity and scale of the project (ACI 506.4R).

Qualification tests may be repeated during construction when the source of shotcrete materials, batching methods, or shotcrete personnel changes. Mill analyses for cement, batch receipts for aggregates, and admixture supplier information usually satisfy the requirements for receipt inspection and acceptance. Daily inspection of both mass- and volumetric-batching equipment may be necessary depending on the overall scale of production. Inspection of the excavation heading should typically take place on a preplacement and post-placement basis as part of the acceptance process. To the extent external conditions affect batching or delivery to the project site, hot or cold weather precautions should be implemented and subjected to inspection and testing. Where testing is required to confirm early-age shotcrete strength for initial support, specific efforts should be made to provide test panel specimens and the subsequent means of curing and

Table 11.2.1—Scope of activities recommended for shotcrete acceptance inspection program

Activity	Project magnitude		
	Complex project	Moderate project	Minor project
Before construction: sampling and testing of shotcrete materials	Complete prequalification of required properties	On selected critical properties	Not required; use of proven material as specified
Before construction: inspection and calibration of batching equipment	In accordance with ASTM C94/C94M or ASTM C685/C685M	Regular inspection at intervals established by the owner or the owner's representative	Not required
Before construction: shotcreting equipment, skill of the crew, and procedures	Preconstruction testing on panels and large-scale mockups (final lining only)	Preconstruction testing on panels and reference projects of similar size and complexity	Qualified or certified nozzleman (ACI CPP 660.1)
During construction: inspection of shotcrete materials	At established intervals for selected critical properties on a shift (daily, weekly, or monthly basis)	Regular inspection at intervals established by the owner or the owner's representative	Initially, then at random
During construction: inspection of batching operations with checks for yields	Full time	Regular inspection at intervals established by the owner or the owner's representative	Random
Inspection of preplacement and placement activities (including curing)	Full time	Regular inspection at intervals established by the owner or the owner's representative	Regular inspection of placement activities at intervals established by the owner or the owner's representative
Monitoring of shotcrete maturity using test panels, in-place cores, and evaluation of shotcrete using nondestructive testing programs	Comprehensive	As needed	Contractor submits test samples
Laboratory tests of shotcrete cores, cubes, or beams for acceptance of shotcrete performance	Fully required	Fully required	Shotcrete strength only

transporting. This can cause logistical and scheduling problems when construction operations take place on a 24-hour basis. Alternatively, methods such as penetration needle and stud driving methods can be used in place or on test panels.

11.2.1 *Duties of inspection team*—Whereas the basic approach is the same, detailed duties and emphasis may vary for the inspection forces involved in small to large projects (Table 11.2.1). The owner's inspection force will often place emphasis on inspection of the finished structure, inspection of shotcrete materials as they are delivered to the project, and testing of the fresh shotcrete and hardened shotcrete. On the other hand, the contractor's quality control inspection force will emphasize inspection of materials, production processes, and placement of reinforcement. These are the most frequently encountered assignments:

(a) Identification, examination, and acceptance of shotcrete materials. This includes verification of quality based on certifications and test results from producers and suppliers, as well as sampling and testing of materials delivered to the job site

(b) Control of mixture proportioning and adjustments, batching, and consistency testing

(c) Examination of the tunnel heading and all surfaces to receive shotcrete, including structural steel, reinforcing steel, embedded items, ground surface preparation, control of water flow, and other preparatory work

(d) Inspection of batching, mixing, conveying, placing, finishing, curing, and protection of shotcrete

(e) Inspection of other support elements, such as lattice girders, rock bolts, welded wire reinforcement, or steel sets, that are an integral part of or affect the installation of the shotcrete lining

(f) Preparation of any required test panels or acquiring in-place shotcrete specimens for laboratory tests and curing and protection of these specimens

(g) General observation of the contractor's plant and equipment, tunnel conditions, external weather conditions, and other items affecting shotcrete or other related parts of the underground opening

(h) Evaluation of test results and performance charts

(i) Verification that unacceptable items (that is, defective shotcrete) and procedures are corrected

(j) Preparation of records and reports

(k) Documentation of sequence and timing of shotcrete placement and subsequent testing

11.2.2 *Qualifications of inspectors*—Inspectors should be individuals who have both practical experience and technical understanding of the principles involved in the assigned construction. They should know the technical requirements required for nozzleman certification. Inexperienced but technically trained individuals should serve for a period of on-the-job training under the supervision of more experienced individuals before working alone.

11.2.3 *Experience, education, and certification of inspectors*—Inspectors need knowledge of and experience in quality control to ensure effective and efficient shotcrete placement for underground support. Inspectors should have some general experience in underground construction, specifically excavation and ground support installation; preferably have worked or been certified as nozzlemen; and have

the benefit of supervisory experience in batching, handling, and testing of shotcrete. Inspectors should be observant, able to evaluate the relative importance of various work items and provide greater attention to important matters.

Inspectors should be completely familiar with all acceptance criteria of the contract documents. Inspectors should be capable of promptly documenting and reporting nonconformances to the contractor's and their own supervisors. Certification of inspectors and technicians is typical and should be mandatory for medium-to-large underground construction projects. Training and certification provide third-party assurance that the inspector or technician possesses at least basic skills and knowledge to perform the job. ACI provides certification for shotcrete nozzlemen, shotcrete inspectors, and for several grades of field and laboratory concrete technicians.

11.3—Specific inspection and testing quality control requirements for underground shotcrete

Much of the background needed to produce a shotcrete system for ground support is provided in this guide. The information in the next few paragraphs is a summary of important points to guide project quality control personnel during the inspection and testing of shotcrete used for underground support. Guidelines and checklists for troubleshooting problems with shotcrete are given in Mahar et al. (1975). Though the following paragraphs address quality control for the complex project, they apply in a general, but less comprehensive, way to moderate and minor projects.

11.3.1 *Study of project drawings and specifications*—The project contract documents are the main criteria governing the decisions and actions of an inspector; therefore, a clear understanding of the specifications and drawings is essential. The project drawings and specifications constitute the basis of all acceptance and rejection criteria.

The inspection staff should know and understand the project drawings and specifications and correctly apply the project acceptance and rejection criteria. Lack of understanding on the part of the inspection or testing staff can lead to inconsistent application of the acceptance criteria. Inspectors should know all permissible tolerances and procedures required to document, record, and report the project work. The owner/engineer's inspection staff should also become familiar with the contractor's plant, calibrations, equipment, personnel, organization, and methods.

The owner's inspection staff should also be aware that in case of critical or emergency conditions at the tunnel face (that is, instabilities or raveling ground), it might be necessary to waive some quality criteria and emphasize the need to get shotcrete support installed quickly to mitigate the risk of greater damage.

11.3.2 *Shotcrete proportioning*—The inspection staff should understand the process and details regarding the type and selection of constitutive shotcrete materials, including tests of aggregates discussed in Chapter 4. Similarly, inspectors should understand the means of proportioning the shotcrete mixture, including mixture computations (grading of mixed aggregates, cement content, *w/cm*, batch quantities, and yield).

11.3.3 *Selection, acceptance inspection, and testing of ground support materials*—In addition to a general background and experience with all ground support materials (specifically shotcrete), the inspection staff should understand the process and details concerning the receipt inspection, identification, and recording of quality; acceptability; uniformity; storage conditions; handling methods; and disposal of wasted, contaminated, or damaged materials. The inspection staff should be experienced with the materials tests shown in Table 11.3.3.

11.3.4 *Tunnel inspections before shotcreting*—The first, and most important, inspection involves inspection of the tunnel or excavation heading to ensure that conditions are sufficiently safe for ground support installation. This should take place after the contractor has scaled or removed loose material from the excavation profile. The line, grade, and profile should be inspected for tights or overbreak to determine if excavation tolerance and tunnel line and grade comply with the project drawing and specifications. The

Table 11.3.3—Acceptance inspection and testing of ground support materials

Material	Test type	Tested elements
Aggregates	Acceptability	Grading, organic matter, deleterious substances, soundness, and resistance to abrasion
	Control	Includes moisture absorption, specific gravity, and density; refer to ASTM C33/C33M
	Assessment	Storage conditions, protection from dampness
Cements, pozzolans, and admixtures	Sampling for laboratory tests	Refer to ASTM C1436
	Assessment	Storage conditions, protection from dampness
Structural and reinforcing steel: steel sets, lattice girders, and other reinforcement	Acceptance inspection	Size, section, weight, bending, surface condition, condition of connections, such as butt plates and accessory bolts
Rock bolts		Length and type (mechanical or grouted)
Fixtures, such as bolts, plates, tie rods, and collar braces		Size, section, weight, condition
Welded wire reinforcement		Size, section, weight, condition
Other materials, such as epoxy resins and cementitious grouts for rock bolt installation, and lagging and blocking		Storage conditions, protection from dampness

inspection should include the location, dimensions, shape, drainage, and preparation of surfaces, and, if applicable, installed reinforcement.

11.3.4.1 *Inspection of surfaces*—Preshift inspections of underground work areas are a mandatory part of any underground construction program. The owner's inspector is not responsible for contractor safety. The inspector is responsible, however, for determining if the surfaces to receive shotcrete are appropriately cleaned and ready. The inspection is typically carried out by the supervisor for the work activity and may or may not be part of a regulated process.

11.3.4.2 *Preparation of surfaces*—Work involved with the preparation of surfaces is discussed in Sections 16.2 and 16.3. The inspector should ensure that these processes are carried out. In cases where a waterproofing membrane is installed on top of the surface, additional smoothness and other requirements may apply.

11.3.4.3 *Reinforcement in place*—Inspection items may include: size (diameter, length, bends, and end anchorage); location (number of bars, minimum clear spacing, and minimum coverage); splicing; stability (tie wire, chairs, and spacers); and openings not shown on drawings.

11.3.4.3 *Waterproofing membrane in place*—Inspection items may include: proper fixation, sagging, welded seams (visual inspection and testing), and repair of punctures. After installation of reinforcement on top of the membrane, an additional inspection before shooting (or casting) the final lining should be conducted to detect punctures of the membrane. In general, welding, burning, and cutting of reinforcement should be avoided or special protection measures must be used to prevent puncture of the membrane and fire hazard. For detailed information about shotcrete application over sheet waterproofing membrane, please refer to "ASA Underground Committee Position Statement #2".

11.3.5 *Tunnel inspections during shotcreting*

11.3.5.1 *Shotcrete placement*—The following inspection items should be considered:

(a) **Work conditions:** Preparations completed, specified interval since previous placement, lighting, covering, and protection (Fig. 11.3.5.1 is a photograph of a well-lighted tunnel heading)

(b) **Batching:** Cement and supplementary cementitious materials, aggregates, water, and admixtures. Batching devices and yield of shotcrete checked

(c) **Control of consistency:** Observations of mixture being shot, tests, and adjustments to water and admixtures in mixture

(d) **Monitoring of air content** in the hopper and out of the nozzle (for wet-mix shotcrete only)

(e) **Mixture temperature**

(f) **Accelerator dosage**

(g) **Conveying:** No segregation of materials; no excessive stiffening or drying out; time limits (can use hydration control admixtures to eliminate these problems)

(h) **Placing:** Materials (acceptability and quantities); condition of equipment; preliminary mixing pressures (air and water); preparation of surfaces; application (nozzle distance and angle; thickness; no sagging, no embedment of rebound; full embedment of reinforcement; no spalling; no construction joints are required at the end of a shift except when required at the end of a shift); no separation at waterproofing membrane; surface finish; curing; and testing schedule. For fresh shotcrete, deficiencies observed should be reported at time of placement

Fig. 11.3.5.1—Well-lighted tunnel heading.

11.3.5.2 *After shotcrete placement*—Inspection items may include: protection from damage, impact, and vibration; rebound removal and clean-up; curing (surfaces continuously moist; time when curing begins; length of curing period [hot or cold conditions]); applied thickness; deficiencies of hardened shotcrete after placement; and repair and rehabilitation of defective shotcrete.

11.3.6 *Inspection records and reports*—Records and reports may include: materials; mixture computations; batching and mixing, placing, and curing; testing results; daily summary reports; diary; and photographs marked with date, station, and direction.

11.4—Cold placement conditions

Special care is required in inspecting shotcrete under cold conditions. It may be necessary to limit shotcreting to acceptable temperatures and times. Other items for inspection include: heated storage bins that prevent freezing of materials; heating materials (use of hot water), contact surfaces, and enclosure; protection of materials from freezing, drying, carbonation, and carbon dioxide; special preparation of rock surfaces; and special measures to prevent freezing and to promote improved curing.

11.5—Hot placement conditions

Special measures are also required in inspecting shotcrete under hot conditions. Items for inspection include: cooling materials; prewetting aggregates and contact surfaces; protecting concrete; and limiting combinations of ventilation, relative humidity, and ambient temperature.

11.6—Shotcrete acceptance and rejection

The acceptance or rejection of fresh and in-place shotcrete is typically subject to inspection, testing, and acceptance on the part of the project QA/QC organization responsible for such activities.

In-place shotcrete is considered acceptable when all inspection and testing reports required by the project QA/

QC program verify that the performance requirements identified in the project specifications and drawings have been satisfied.

Specific deficiencies can include but are not limited to: excessive voids; debonding from receiving surface or structure; delamination; improper encapsulation of reinforcement or other support members, laitance, sand pockets, or trapped rebound; cracking, sloughing, or spalling; low compressive strength, density, or high permeability; or deficiency in another property considered critical to performance.

Such deficiencies can only be determined by means of inspection, testing, and evaluation, as noted previously, in accordance with project QA/QC procedures, as specified by the project engineer.

11.7—Recommended specifications

Recommended specifications for inspection are provided in Table 11.7. 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 11.7—Example guide specification for inspection

Section/ Part/ Article	Recommended specification language	Notes to the Specifier
11.1	*Shotcrete materials testing*	
11.1.1	For mixtures weight-batched on site, regularly monitor aggregate grading and moisture content. One moisture content check shall be made at the startup of each shotcreting operation and with any indication of change in aggregate moisture content.	The suggested frequency is daily unless moisture content obviously has not changed.
11.1.2	For dry-bagged, premixed materials, conduct washout testing to check cementitious content, aggregate grading, and fiber content in fiber-reinforced shotcrete, at the frequency specified by the engineer.	The suggested frequency is one washout test after each delivery of dry-bagged premixed materials until quality is confirmed.
11.1.3	For mixtures volume-batched on site, check aggregate moisture content and mixture proportions at the frequency specified by the engineer.	The suggested frequency is daily unless moisture content obviously has not changed.
11.1.4	Perform physical testing for the hardened shotcrete performance parameters specified in the contract documents, at the frequency specified by the engineer.	The suggested frequency is every 40 yd^3 (30 m^3), or for each day's shooting.
11.2	*Construction testing*	Sampling and testing of shotcrete at established intervals during construction is usually required. If nozzlemen are working in multiple shifts, each nozzleman should comply. In large, long-lasting projects, the frequency of testing may be relaxed at the discretion of the owner or the engineer, if consistently compliant test results are demonstrated during initial construction and testing.
11.2.1	Shoot one construction test panel for each nozzle orientation for each day of shotcrete production, or every 50 yd^3 (40 m^3) of shotcrete, whichever is more frequent.	
11.2.2	Test panels shall have the same dimensions as preconstruction test panels but shall contain no reinforcement or embedments (other than fiber reinforcement).	Refer to Example Specification and Notes to the Specifier Section 10.2.4.
11.2.3	For each test panel shot, keep a record of date/time shot, shotcrete mixture, personnel shooting panel, temperature and weather conditions, date panel shipped, and date received by laboratory.	
11.2.4	Test specimens shall be prepared and tested in the same manner prescribed for preconstruction test specimens. Store, handle, and cure construction test panels in the manner prescribed for preconstruction test panels.	Refer to Example Specifications and Notes to the Specifier Sections 10.2.5 through 10.2.10.
11.2.5	Adjust measured compressive strengths to equivalent 2:1 length: diameter cores, using the core correction factors given in ASTM C42/C42M. Three 3 in. (75 mm) diameter cores shall be tested at both 7 and 28 days.	In addition, if early strength is important, strength test will also be conducted at the age of 8 hours or as otherwise specified by the engineer.
11.2.6	The mean compressive strength for a set of three cores from test panels shall equal or exceed the specified strength.	
11.2.7	Specimens for boiled absorption and permeable voids testing to ASTM C642 shall be 4 in. (100 mm) cubes cut from the broken ends of flexural test prisms or extracted 3 in. (75 mm) diameter cores at least 4 in. (100 mm) long. Test three specimens, starting the test 7 days after shooting.	

Table 11.7, cont.—Example guide specification for inspection

11.2.8	Early strength shall be tested either in-place or at test panels with penetrometers and/or stud driving method. For each test, keep a record of date/time shot, shotcrete mixture, personnel shooting panel, temperature and weather conditions, and test result, especially if used for re-entry criteria.	Often, a certain early strength tested with a penetrometer or stud driving method as re-entry criteria is used when the shotcrete strength is insufficient to allow for extraction of cores. The tests are quick, easy, and provide a good indication if there are problems with the strength development. However, test results need to be properly documented. The tests are a crude correlation to the in-place compressive strength and a representative number of tests need to be completed. Criteria for pass/fail should be established by the contractor, as the early-age strength impacts the construction schedule and generally does not have an impact on the final strength or durability properties.
11.3	Inspection/acceptance: Using Table 11.2.1, create specifications based on project size and complexity.	Acceptance inspections should be sufficiently frequent and detailed to permit adequate evaluation of the shotcrete process and the products resulting from that process.
11.4	*Acceptance*	
11.4.1	Shotcrete that does not conform to the specifications may be rejected by the owner either during the shotcrete application process or based on tests on test panels or on the completed work.	Refer to 11.6 for a definition of deficient shotcrete.
11.4.2	Deficiencies observed during the shotcrete application include, but are not limited to: (a) Failure to properly control and remove buildup of overspray and rebound (b) Incomplete embedment of reinforcing steel and anchors by shotcrete (c) Excessive shotcrete rebound, or fiber rebound (d) Incorporation of excessive voids, sand or rock pockets, delaminations, or laitance (e) Failure to apply shotcrete to the required thickness (f) Cracking, sagging, or sloughing (g) Unacceptable strength, density, permeability, or a deficiency in another property critical to performance	Refer to 11.6 for a definition of deficient shotcrete.
11.4.3	Perform remedial work to correct deficiencies while the shotcrete is still fresh.	Fresh shotcrete is more easily removed than hardened shotcrete.
11.4.4	The engineer shall examine the hardened shotcrete for any evidence of excessive plastic or drying-shrinkage cracking, tears, feather edging, sloughing, or other observable deficiencies.	Sounding rod or hammer should be used to check for delaminations and debonded shotcrete.
11.4.5	If the results of compliance tests from shotcrete test panels or assessment of the in-place plastic and hardened shotcrete indicate nonconformance of the shotcrete to the specifications, the engineer will implement a program of evaluation of the in-place shotcrete. Such evaluation may include, but not be limited to: (a) Extraction of cores from the in-place shotcrete and testing of such cores for compliance to the project specifications (b) Checking for delaminations or debonded shotcrete using sounding or other appropriate nondestructive testing procedures (c) Diamond saw-cutting or coring to check the adequacy of encasement of rock bolts and reinforcing bars or welded wire reinforcement.	The disposition of the nonconformance should be commensurate with the complexity and performance requirements of the structure. Destructive tests for final linings should be limited to the absolute minimum, especially if a waterproofing membrane is used.
11.4.6	Shotcrete that is nonconforming shall be removed and replaced by the contractor. Alternatively, if approved by the owner, additional shotcrete shall be applied.	If the project QA organizations determine to accept the shotcrete "as-is," no further remedial action will be necessary.

11.8—Recommended QC Inspection and Testing Checklist

Recommended QC Inspection and Testing Checklist is provided in Table 11.8.

Table 11.8—Underground shotcrete quality control inspection and testing

Details		Inspection during construction	References (ACI documents)	Frequency*
Mixture design	Aggregate moisture content		Mixture batch ticket	Daily
	Aggregate gradation			Once for new source, new production, or once for every 3 months
	Cement certificates			Initial submittal
	Pozzolans/cementitious materials			
	Chemical admixtures			
Materials added on site	Count rotation for mixing, fibers, site-based batching, chemical admixtures			Every truck load
Mixing method of batch plant	Central mixing or truck mixing			Start of the project
	Batch time, delivery time			Every truck load
Wet-mix delivered materials' temperature	Temperature			Every truck load
Bagged dry-mix	Temperature			Every 50 yd^3 (40 m^3) or daily
Wet-mix slump				Every truck load
Wet-mix air content				Every 50 yd^3 (40 m^3)
Structural and reinforcing steel prior to placement	Steel set	Rigidity, alignment, coverage, splicing		Daily
	Lattice girders			
	Welded wire reinforcement			
	Other reinforcement			
Calibration of batching equipment	—	—	ASTM C94/C94M or ASTM C685/C685M	Before construction and during construction (once for every month)
Verification of accelerator use	Rate of accelerator to shotcrete volume	Accelerator dosage		Daily
Verification of predempener operation, if used				Daily
Yields			Concrete mixture design and specification	Initial submittal
Surface preparation	Scaling, SSD, possible loose behind wire mesh, excessive moisture on the surface, water diversion, lagging and blocking			All the area
Loose wire mesh tightness				All the area
Adequate underground lighting				All the area
Services including air volume, power, water pressure and ventilation				All the area
Application	Proper nozzling techniques			
Finishing	As specified			
Curing (if specified)	Follow manufacturer's instructions			
Shotcrete field and laboratory testing	Air content			As submitted
	Slump			As submitted
	Panel production, handling, curing and protection			As submitted

Table 11.8, cont.—Underground shotcrete quality control inspection and testing

	Compressive strength for cores		ASTM C1604/C1604M	One set of three cores every 50 yd^3 (40 m^3) or everyday shotcrete work
	Penetration needling testing for early-age strength		ASTM C1117	Initial submittal or as specified
	Early-age compressive strength for end beam testing		ASTM C116 modified	Initial submittal or as specified
	Volume of permeable voids and boiled absorption (if specified)		ASTM C642	Initial submittal or as specified
	Flexural toughness for fiber-reinforced shotcrete to ASTM C1609/C1609M (if specified)		ASTM C1609/C1609M	Initial submittal or as specified
	Flexural toughness for fiber-reinforced shotcrete to ASTM C1550 (if specified)		ASTM C1550	Initial submittal or as specified
	Safety protections, including PPE and procedures for re-entry, confined space, or any other site-specific requirement			Follow job safety requirement
	Mine or tunnel information including location, survey markings, levels			

*Note: The testing frequency might be reduced upon satisfactory consistent results and approved by the owner.

CHAPTER 12—BATCHING, MIXING, AND SUPPLY

12.1—Handling of bulk bin-bags

When bulk bin-bags are used, a forklift is typically used to place the bag directly over the hopper of the pre-dampening unit or the shotcrete machine. The bag is opened by pulling on a string, thus allowing the dry material to gradually flow from the bag and into the shotcrete equipment. Silos are also used; they can hold up to six bulk bags at a time and can be placed directly above the hopper. This eliminates the need to have a forklift in the way. It also increases productivity by keeping a consistent supply of material.

12.2—Quality control considerations

There are several advantages to dry-packaged supply over traditional central or transit mixers:

(a) With use of proper plastic shrink-wrapping, materials can be stored outside for months without any risk of deterioration as long as temperatures are within acceptable limits of 40 to 85°F (5 to 30°C)

(b) Greater control of quality is possible because materials are proportioned by mass and without any influence of moisture

(c) There is no risk of premature cement hydration that can be caused by moist aggregates in the dry-mix process whenever an accelerator admixture is used

There are also some quality control disadvantages to dry-packaged supply:

(a) Storage facility or space is needed

(b) Product temperature needs to be maintained if stored on site for long periods

(c) There is the risk of rainwater or snow penetrating through the bags of material (covers are needed).

12.3—Recommended specifications

Recommended specifications for batching, mixing, and supply are provided in Table 12.3. 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.

Table 12.3—Example guide specification for batching, mixing, and supply

Section/ Part/ Article	Recommended specification language	Notes to the Specifier
12.1	Batching, mixing, and supply: wet-mix shotcrete	
12.1.1	General: Wet-mix shotcrete shall be batched, mixed and supplied using one of these systems: (a) Central mixing with transit mixture delivery (b) Transit mixing and delivery (c) Volumetric batching, mobile mixer unit (d) Packaged, preblended, dry, combined materials with water added on site.	Logistics and cost usually dictate the method selected by contractor. Note that volumetric batching requires more inspection by the owner.

Table 12.3, cont.—Example guide specification for batching, mixing, and supply

12.1.2	*Central mixing and supply*	
12.1.2.1	Aggregate, cement, and supplementary cementitious materials and fibers shall be mass batched in a central mixing plant and delivered in a transit mixer in accordance with the requirements of ASTM C94/C94M or C1116/C1116M. Water and chemical admixtures shall be either mass or volumetrically batched. Weighing equipment shall be capable of batching to the accuracy specified in ASTM C94/C94M.	
12.1.2.2	Add shotcrete materials, including fibers, in a sequence that ensures uniform mixing and dispersion.	
12.1.2.3	Transit mixers shall be free of accumulations of hardened shotcrete or concrete in the drum or on the blades. Blades shall be free of excessive wear. Transit delivery shall conform to the requirements of ASTM C94/C94M.	
12.1.2.4	One retempering with high-range water-reducing admixture added directly to the transit mixer during the period of discharge shall be permitted to maintain workability (slump) of shotcrete within the specified range of 3 ± 1 in. (80 ± 30 mm). Mixing shall continue for a minimum period of 5 minutes at rated mixing speed after adding high-range water-reducing admixture to the transit mixer.	
12.1.2.5	All shotcrete shall be shot within 90 minutes after addition of mixing water to the batch unless otherwise approved; special set-retarding or hydration-controlling admixtures are used to extend the working life of the shotcrete. Scheduling of shotcrete delivery and shotcrete load size shall be such that this requirement is met.	
12.1.3	*Transit mixing and supply*	
12.1.3.1	The same requirements shall apply as specified for central mixing except that all ingredients shall be added directly to the transit mixer. Transit mixers shall be charged to not more than 70% of their rated capacity, to enable efficient mixing action.	
12.1.4	*Volumetric site batching*	
12.1.4.1	The mobile mixer unit for volumetric site batching shall conform to the requirements of ASTM C685/C685M.	
12.1.4.2	The equipment shall be capable of thoroughly mixing materials in sufficient quantity to maintain shotcreting continuity.	
12.1.4.3	Calibrate equipment in accordance with the requirements of ASTM C685/C685M at the start of every shift or for every 50 yd^3 (40 m^3) of shotcrete batched, whichever is more frequent, using a mass batch check of the volumetric proportioning.	Requires inspector to have the time and proper equipment to accomplish.
12.1.4.4	Feed systems for all materials (cement, supplementary cementitious materials, aggregates, admixtures, and fibers) shall be interconnected such that if one feed stops or changes rate, they all follow.	
12.1.4.5	Thoroughly clean equipment at least once per shift to prevent accumulation of aged material.	
12.1.4.6	Apply shotcrete within 90 minutes of mixing unless approved, special set retarders or hydration-controlling admixtures are used to extend the working life of the shotcrete. Aged material shall be discarded and not applied in the work.	
12.1.5	*Packaged, preblended, dry, combined supply*	
12.1.5.1	The use of packaged supply with water addition at the site shall be permitted, provided the contractor can demonstrate uniform mixing of the shotcrete and satisfactory conformance to all the project performance requirements.	
12.2	*Batching, mixing and supply: dry-mix shotcrete*	
12.2.1	*General*	
12.2.1.1	Dry-mix shotcrete shall be batched, mixed, and supplied by one of these methods: (a) Site batching using volumetric batching units (b) Site batching using mass batching units and rotary transit mixer supply (c) Packaged, preblended, dry, combined material supplied in either small paper bags or large, synthetic cloth, bulk bin-bags	

Table 12.3, cont.—Example guide specification for batching, mixing, and supply

12.2.2	*Volumetric site batching and supply*	
12.2.2.1	The same criteria specified in Example Specification 12.1.4 for volumetric site batching for wet-mix shotcrete shall apply for dry-mix shotcrete, except that all dry-mix shotcrete shall be shot within 45 minutes of first contact of cement with moisture.	
12.2.3	*Mass batching and supply*	
12.2.3.1	The same criteria specified in Example Specification 12.1.2 for central mixing and supply of wet-mix shotcrete shall apply for dry-mix shotcrete, except that the bulk of the water shall be added at the water ring at the nozzle during the shotcrete application process, and all dry-mix shotcrete shall be shot within 45 minutes of first contact of cement with moisture.	
12.2.4	*Packaged, preblended, dry, combined batching and supply*	Preblended desiccated shotcrete can be supplied on site containing all the necessary ingredients accurately dosed (fibers and accelerator included) in either small paper bags (typically 65 lb [30 kg]) or large plastic bulk bin-bags (up to 3300 lb [1500 kg]). This is usually the supply method of choice for remote areas or mines and tunnels using the dry-mix process. Refer to Section 12.1.
12.2.4.1	Packaged shotcrete shall be mass-batched in conformance with the requirements of ASTM C1480/C1480M. All aggregates shall be dried to a moisture content of less than 0.1% by mass, based on oven drying at 220 to 230°F (105 to 110°C).	
12.2.4.2	Protect packaged shotcrete from exposure to moisture during handling, transport, and storage. Discard any bags that display lumps of prehydrated shotcrete.	Refer to Section 12.2.

CHAPTER 13—PLACING EQUIPMENT

13.1—General

Machines for both wet-mix and dry-mix shotcrete placement are capable of delivering an adjustable flow of concrete materials through a delivery line to a nozzle.

13.2—Pumps for wet-mix

The development of concrete pumps suitable for wet-mix shotcrete delivery has allowed many innovations in the use of shotcrete for underground construction. Several types are acceptable, including continuous cavity, peristaltic tube, pressure vessel, and rotary machines that operate similarly to dry guns. Nevertheless, the hydraulic, twin-piston type of concrete pump is most commonly used. Figure 13.2a is a diagram of piston-type pump, and Fig. 13.2b is a photograph of a peristaltic type.

The concrete pump selected for shotcrete application should be capable of pumping materials from the larger-diameter material cylinders to and through reduced-diameter conveying lines and providing continuous flow to the nozzle system at the exit end. Manufacturers should be consulted regarding operation and suitability for specific shotcrete mixtures and applications. As in the dry-mix, the machines used for placement of wet-mix shotcrete are metering devices, and proper operation does not alter the materials. The mixture proportions in-place will be different from the as-batched proportions, however, because of rebound and a reduction in the air content of air-entrained shotcrete during pumping.

If large quantities of wet-mix shotcrete, accelerated with liquid accelerators, are used, an accelerator pump that is controlled by, and automatically synchronized with, the concrete pump is recommended.

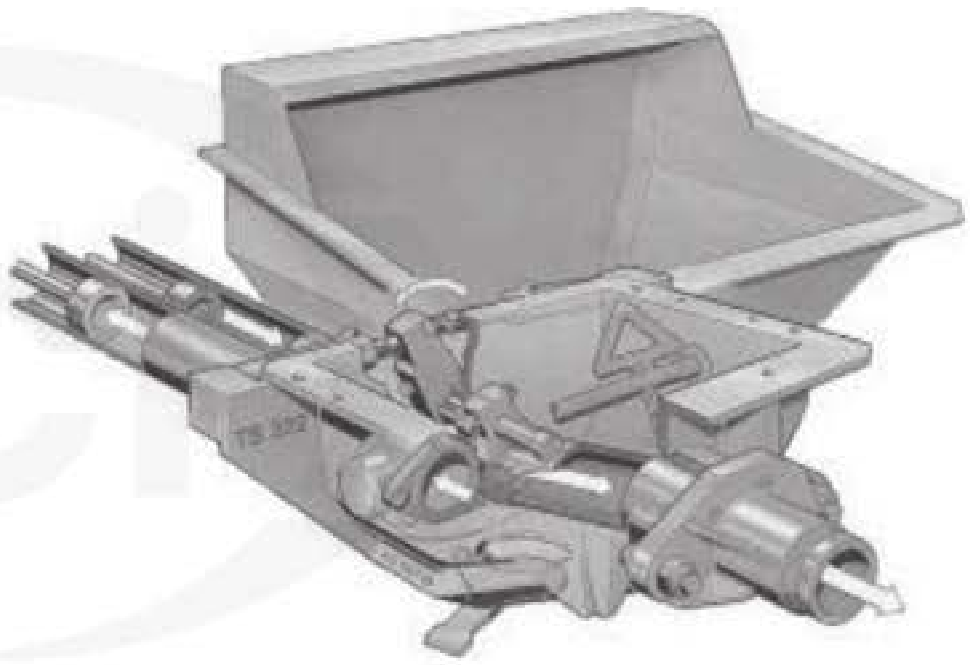

Fig. 13.2a—Piston-type pump.

Fig. 13.2b—Peristaltic-type pump.

13.3—Guns for dry-mix

Dry-mix equipment historically consisted of double-tank, pressure vessel-type guns, followed by rotary barrel machines, and then bowl-type machines. All are acceptable for shotcrete application, and all are designed to meter material into a moving air stream that passes through the

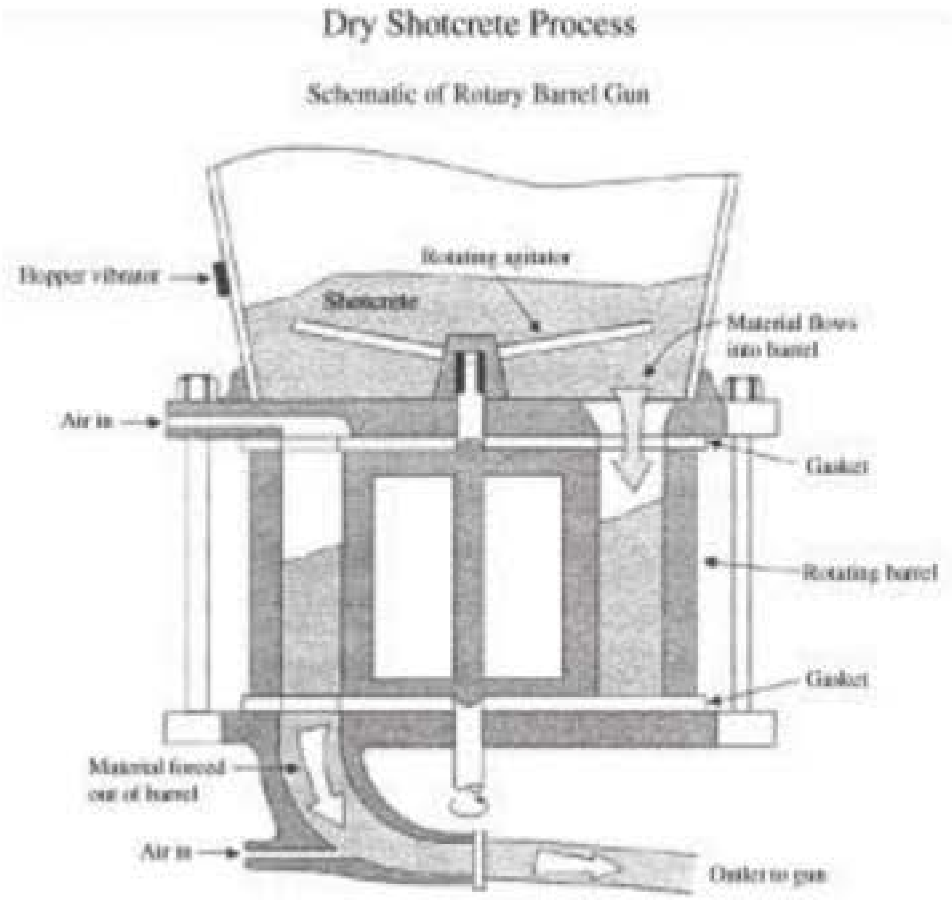

Fig. 13.3—GM57: rotary barrel gun with cutaway view.

machine. Figure 13.3 is a photograph of a typical rotary barrel machine. A description of the principle can be found in ACI 506R and in manufacturers' literature. Proper operation of all dry shotcrete machines does not appreciably alter the condition or consistency of the materials that are delivered into or through the equipment. Proper installation, operation, and maintenance are essential, however, for acceptable shotcrete application.

13.4—Nozzle systems

The nozzle system in both dry-mix and wet-mix shotcrete methods is an important component of the process. The dry-mix nozzle is a mechanism attached to the end of the conveying hose that consists of a water input chamber and water ring designed to inject water into the passing material stream. The water control valve fitted to the chamber should be convenient for the operator and accurate in the control of injected water. The nozzle tip is configured to briefly upset the flow of material and provide turbulence for mixing the water and material before jetting it into place on the substrate. There are various styles suitable for application. Choices should be made on the basis of experience and performance suited for the specific application.

Nozzle systems for wet-mix application are complex in their function. They should receive a flow of material that is extruded from a concrete pump at a speed of 3 to 6 ft/s (1 to 2 m/s) and be provided with adequate air input to interact with the material stream. Nozzle systems then expel the material at high velocity—approximately 60 to 100 ft/s (20 to 30 m/s) (Ginouse and Jolin 2013)—in a uniform spray to impact the substrate and thoroughly compact the material placed. The air flow is critical to all the transport and spray aspects of the shotcrete process. Therefore, a wet-mix nozzle should provide a means to input adequate air flow to increase the velocity of the material stream to ensure proper impact to the substrate. Nozzle systems for wet-mix shotcrete employ an air ring/sleeve component that is exposed

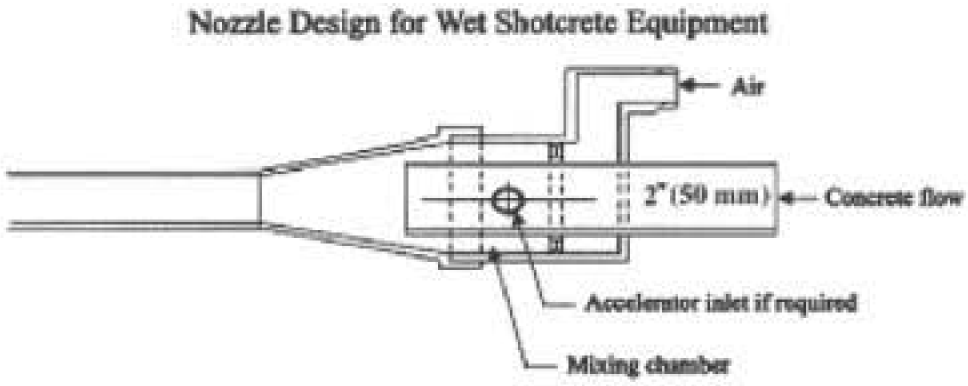

Fig. 13.4a—Diagram of wet-mix nozzle.

Fig. 13.4b—Close-up of wet-mix nozzle.

to concrete and chemical accelerators that can clog the air holes. Figure 13.4a is a schematic diagram, and Fig. 13.4b is a close-up photo of a wet-mix nozzle. Care should be given to cleanliness and proper maintenance of this section of the nozzle.

The injection of accelerators is another very important function of the nozzle. Usually, but not always, a liquid accelerator is injected at the nozzle. Care should be taken to ensure proper dispersion of accelerator in the material stream (usually by injecting admixture into the airstream before entry in the nozzle body) and to ensure that the rate of accelerator addition is known and reliable. On large projects, an accelerator pump synchronized with the concrete pump is essential. Calibrating the accelerator dosage with the pump rate is challenging because the air pressure as well as the concrete influence the pressure conditions in the nozzle and, thus, the pump rate/accelerator dosage. When shooting in dripping or flowing water situations, the nozzle may be configured so that the nozzleman can control the accelerator dosage. However, the accelerator dosage should be closely controlled and documented by supervising staff (Zhang 2012).

Supplementary nozzle systems can be employed in both wet-mix and dry-mix applications. In the dry-mix process, they can be used to increase water addition some distance before exit. In the wet-mix process, supplementary nozzle systems are usually used to introduce air to loosen the materials that are compacted in the concrete pump conveying process. Manufacturers should be consulted for special application information.

13.5—Remote-controlled spraying

Equipment that supports and manipulates the shotcrete nozzle system and is capable of operation from a remote position is available and desirable for underground shotcrete

applications. The mechanical, remote-controlled units can be employed for both dry-mix and wet-mix applications. A primary reason to use this application method is safety, in that the nozzleman may place shotcrete in an unsupported ground area in a mine or tunnel. For the wet-mix shotcrete process, the inherent capacity of a hydraulic assisted or mechanical system can be exploited to considerable advantage. Figures 5.5b and 13.5 are photographs of typical remote-controlled shotcreting systems in a tunnel.

Fig. 13.5—Deployment of robotic nozzle in large tunnel.

Nozzlemen not familiar with the equipment should be properly trained and given time to practice before shooting critical elements of a project. If remote-controlled spraying is used on a project, all preconstruction and qualification testing should use the equipment during the tests to provide representative results.

13.6—Recommended specifications

Recommended specifications for placing equipment are provided in Table 13.6. 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 13.6—Example guide specification for placing equipment

Section/Part/ Article	Recommended specification language	Notes to the Specifier
13.1	*Wet-mix shotcrete delivery equipment*	
13.1.1	Wet-mix shotcrete shall be applied by the thick-stream method.	Thick stream involves the use of a concrete pump suitable for transfer of the shotcrete through the hose, with the addition of air at the nozzle, to pneumatically apply the shotcrete onto the receiving surface at high velocity.
13.1.2	Shotcrete shall be applied by either hand-held or robotic nozzle (remote-controlled booms).	Where a fully mechanized robotic unit is impractical, a man lift can be employed (except in very small openings) to reduce nozzleman fatigue and improve uniformity of cover.
13.1.3	The delivery equipment for wet-mix shotcrete shall be capable of delivering a steady stream of uniformly mixed material to the discharge nozzle.	The use of positive displacement concrete pumps consisting of two hydraulically or mechanically driven cylinders and a quick changing valve capable of delivering a constant flow of material to the nozzle is recommended. Alternative pump types, such as pneumatic feed, peristaltic tube, and continuous cavity, may be submitted for approval, provided that the contractor can demonstrate that they produce shotcrete that meets all the performance requirements of the specification.
13.1.4	The nozzle system employed shall be of a design that allows sufficient throughput of air to interact with the flow of material and produce a spray at sufficiently increased velocity for the shotcrete to impact the receiving surface and fully compact the material in place.	Generally, air flow is 250 to 400 ft^3/min (7 to 11 m^3/min).
13.1.5	The nozzle system employed shall be of a design that permits the introduction of accelerating admixtures into the shotcrete either in the air stream or through a separate inlet.	
13.1.6	If liquid accelerator is used, the accelerator pump shall be controlled by, and synchronized with, the concrete pump. Project-specific calibration and periodic recalibration is required.	Accelerator can have very detrimental effects on the shotcrete quality if overdosed. It is therefore necessary to not allow for manual or ad hoc adjustments to the dosage rate by the crew. Calibration of the pump is also dependent on the air pressure used and should be considered.
13.1.7	The nozzleman and crew shall monitor the air ring and nozzle system of the nozzle for any signs of nonuniform flow of material caused by dirty or blocked holes in the air ring.	If unacceptable changes in material flow occur, work should be stopped, and appropriate maintenance steps should be performed.
13.1.8	The delivery equipment shall be thoroughly cleaned at the end of each shift or placement operation.	Particular attention should be given to the removal of shotcrete buildup in the pipe and hose system. The air ring and nozzle system should be regularly inspected, maintained, and replaced as required.

Table 13.6, cont.—Example guide specification for placing equipment

13.2	*Dry-mix shotcrete delivery equipment*	
13.2.1	Dry-mix shotcrete delivery equipment shall be capable of metering semi-dry mixtures into a moving air stream of sufficient volume to convey the material through the hose system and propel the mixture onto a surface at high velocity. The type of equipment shall be chosen and outfitted to properly suit the application. The contractor shall submit the equipment type to be used and be capable of demonstrating suitability.	The equipment for dry shotcrete application may be of various types, including double-chamber pressure vessel, rotary, and bowl.
13.2.2	Dry, bagged, premixed materials shall be predampened, using a suitable machine, to provide consistent moisture content in the range of 3 to 5% by mass, before discharge into the shotcrete gun. Alternatively, a water ring system placed 10 ft (3 m) before the exit nozzle may be used, provided uniform predampening of shotcrete can be demonstrated. The use of desiccated materials with a water ring only at the exit nozzle shall not be permitted.	The use of desiccated materials with a water ring only at the exit nozzle should not be considered acceptable shotcrete practice. Experience shows that predampening leads to less dust emission, less rebound, and a more homogeneously mixed shotcrete material. If predampening equipment is not available, the alternative described (hydromix nozzle) provides longer mixing of water mixing into the shotcrete mixture.
13.2.3	Similar to Example Specification Section 13.2.2, for site-mixed materials using sand with too low a moisture content to produce a mixture with a consistent moisture content, then predampening equipment shall be employed to introduce additional moisture.	
13.2.4	The mixing and predampening units shall be capable of producing a shotcrete mixture with a consistently uniform moisture content such that the nozzleman is not required to repeatedly adjust the water content at the nozzle water ring.	
13.2.5	The delivery equipment (gun) shall be capable of metering a continuous, smooth stream of material into the delivery hose at the proper velocity to the discharge nozzle.	
13.2.6	The nozzle system for the dry-mix shotcrete application shall contain a chamber and water ring capable of injecting a controlled amount of pressurized water into the material stream as it passes through. The nozzle shall be fitted with a spray tip designed to cause upset of the stream and create mixing turbulence before discharge onto the receiving surface. The nozzle system shall be fitted with a manual water control that is convenient for operation by the nozzleman.	
13.2.7	The water pressure at the discharge nozzle shall be sufficiently greater than the operating air pressure of the material line so that the water is intimately mixed with the predampened shotcrete materials. If line water pressure is inadequate, a water booster pump shall be introduced into the water system to provide steady, non-pulsating water pressure. Water heaters shall be provided under cold conditions if required to produce shotcrete at a suitable temperature.	Water pressure should exceed air pressure at the nozzle by a minimum of 15 psi (1 bar).
13.2.8	Carefully monitor the water ring for any signs of blocked holes. If non-uniform wetting of discharged shotcrete becomes apparent, stop shooting and clean the water ring or take appropriate corrective action. This is particularly important if liquid accelerator is being added with the mixing water at the nozzle.	
13.2.9	The delivery equipment shall be thoroughly cleaned at the end of each shift or placing operation. Particular attention shall be given to removal of shotcrete buildup in outlets and hoses. The nozzle and water ring shall be serviced regularly, and components replaced as required.	

CHAPTER 14—AUXILIARY EQUIPMENT

14.1—Air supply

Clean, dry air is important to the shotcrete process in both methods. The contractor should give special attention to the filtration system and the general condition of compressor equipment used for shotcreting. Compressors should be sized to provide adequate working air for shotcreting as well as ancillary equipment including blowpipe (air lance). Tools for other work should be connected to a separate air source whenever possible to eliminate disruption of the material flow.

Compressed air available in many underground mines often has variable, but relatively high, moisture contents. Awareness of this situation is important, and removal of or compensation for this moisture content in the mixture proportions may be necessary.

Machines configured as dry-mix shotcrete units are available for wet-mix shotcrete application. Because air is the sole source of conveyance of the plastic material, manu-

facturers of this equipment should be consulted for recommended compressor capacity.

14.2—Recommended specifications

Recommended specifications for auxiliary equipment are provided in Table 14.2. 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.

Table 14.2—Example guide specification for auxiliary equipment

Section/ Part/Article	Recommended specification language	Notes to the Specifier
14	*Auxiliary equipment*	
14.1	Air compressors, dry-mix shotcrete	Compressed air is the medium employed to pneumatically convey the material through the delivery system and onto the surface in the dry shotcrete process. Thus, volume of air, rather than pressure, is more critical to the shotcrete application. The velocity and impact force are directly correlated to the quality (performance) of the placed material. The dry-mix equipment depends on a sufficient air volume source for proper application, as outlined in ACI 506R. Additional information should be solicited from the equipment manufacturer. Additional users of the air supply from the same source (that is, for blowpipes) should be limited and, if cannot be avoided, accounted for.
14.1.1	Air supply shall be of sufficient volume (ft^3/s [m^3/s]) to convey the semi-dry concrete mixture through the delivery system and project the material onto the receiving surface at an acceptable, high velocity.	
14.1.2	Air supply shall be uniform and dedicated to ensure proper, uninterrupted flow throughout the spraying operation.	
14.1.3	Air supply shall be clean and free from water and oil.	Pressure at the source should be 90 to 100 psi (0.6 to 0.7 MPa) as is common with standard compressor equipment used in construction. The working pressure, measured at the gun or along the conveying system, is a measure of resistance of the material load to the incoming air. It will vary according to material composition, line size and configuration, distance, height, and other system variations. Compressor capacities for dry-mix shotcrete applications range from a minimum of 350 ft^3/min (9.9 m^3/min) for a simple, low-volume application to 1000 ft^3/min (28.3 m^3/min) for high-volume underground projects using large aggregate, steel fiber mixtures, or both.
14.1.4	Air lines and fittings shall be of sufficient size (internal diameter) to allow full flow of air from the source, without restrictions that will reduce volume required to convey and propel materials through the nozzle and properly impact the application surface.	
14.1.5	Air equipment shall provide a pressure sufficient to perform the work and products as required by the contract documents.	
14.1.6	Shotcrete equipment that employs air motors for operation shall have separate air line connections so that motor functions do not influence proper transport and application of materials through the delivery system.	Separate air lines reduce the potential for interaction between the two air demands. If separate air lines are not used, the air pressure in the materials line may drop when the shotcrete machine is started.
14.2	Air compressors, wet-mix shotcrete	The wet-mix shotcrete process uses hydraulic pumping to convey the concrete mixture through the delivery system to the nozzle. The speed of ejection is 3 to 6 ft/s (1 to 2 m/s). To propel the particles onto the surface at sufficiently high velocity to achieve the quality and performance characteristics of shotcrete, air should be introduced into the nozzle in a manner to break down the extruded material and increase speed (refer to Chapter 13).
14.2.1	Air supply shall be of sufficient volume (ft^3/min [m^3/min]) to accelerate the flow of material at the nozzle and to create a spray of acceptable high velocity to fully compact the material on the receiving surface.	
14.2.2	Air supply shall be clean and free from water and oil.	
14.2.3	Air lines and fittings shall be of adequate size (internal diameter) to accommodate full flow of air and compatible with the nozzle system employed.	The volume of air, rather than pressure, is the primary requirement of the wet-mix; however, the volume to do the work is considerably less than required for similar dry shotcrete applications. Compressor requirements range from 200 ft^3/min (4.2 m^3/min) for a small-diameter, low-volume repair project to 400 ft^3/min (11.3 m^3/min) for a high-volume, robotic application.
14.2.4	Air supply shall be uniform and dedicated to ensure proper, uninterrupted flow throughout spraying operations.	
14.2.5	Air supply equipment shall provide a minimum pressure of 9 psi (0.6 MPa).	
14.3	Water supply, dry-mix shotcrete	For dry-mix shotcrete, the pressure of the water supply is critical to an adequate mixing of water into the mixture. If the water pressure is too low, the water supply will vary constantly with the air pressure in the hose, causing a heterogeneous in-place shotcrete with characteristic sand layers.
14.3.1	Water supply to the nozzle and pre-moisturizing system shall be clean, potable, and free of any components that are deleterious to portland-cement concrete.	
14.3.2	Water supply to the nozzle shall be of sufficient volume and pressure to ensure at least 15 psi (1 bar) greater pressure at the water ring than the material line pressure. If supply pressure is inadequate, water-pressure-boosting equipment shall be incorporated into the system.	Whenever the water pressure at the point of shotcreting is not high enough, a water booster pump (electric or compressed air driven) should be used to provide adequate water pressure. Lack of available, potable water is frequently an issue for shotcrete in underground mines. Guidelines for the use of recycled or impure water in concrete are available from the Portland Cement Association. As a minimum, any nonpotable water should be tested with the typical shotcrete materials being used to determine suitability in terms of performance of the placed concrete.

CHAPTER 15—SAFETY

15.1—General

A well-defined safety program for shotcrete preparation and application, as well as in all other areas of the operation or project, is imperative if accidents are to be prevented. Accidents and injuries are costly to the injured employee due to temporary or permanent disability and pain, lost income, and mental stress.

Accidents and injuries are also costly to a company because of lost production, lower productivity, fines, higher insurance costs, increased expenses in dealing with increased government inspections, lower employee morale, decreased corporate reputation, and potential exclusion from future projects. The Mine Safety and Health Administration (MSHA) and Occupational Safety and Health Administration (OSHA) ratings are used to screen out contractors with poor safety records during project prequalification.

Not all incidents result in injury or equipment damage. Nevertheless, these "near-miss" incidents should be monitored closely because they serve as an indicator of the potential for actual accidents.

Federal mine safety laws and the MSHA require that all miners receive a specified level of safety and health training annually, and that documentation of this training is maintained on file. The exact nature and content of this training can change; thus, all safety directors, project managers, and superintendents should keep themselves well informed about current regulations.

15.2—Underground safety

Underground work can be potentially more dangerous than surface construction. One of the most critical safety concerns occurs at a freshly excavated or blasted face before the installation of required ground support, particularly where workers end up under any unsupported ground. Shotcrete is often applied and is expected to perform at this critical time.

Rock mechanical considerations, geotechnical considerations, or both, together with the available infrastructure and tools for the application, determine the appropriate level of scaling necessary and the means for safely performing it. Typically, tunnel or mine openings should be properly scaled immediately after excavation and before shotcrete application begins. Scaling of the tunnel walls should also be performed as required during tunnel construction. Rapid application of the shotcrete typically follows scaling as soon as is feasible under operational constraints.

In addition to the potential for rockfall, the shotcrete crew and inspection personnel should also be vigilant for falling shotcrete. Shotcrete applied overhead can fall out and poses a potential safety hazard until the shotcrete has gained sufficient strength. Many factors influencing the potential for fallouts addressed in "ASA Underground Committee Position Statement #1". When shotcrete is applied in layers that are too thick to adhere to the rock surface and there is insufficient time allowed for setting, there is a potential for shotcrete to slough and fall. In areas of poor rock quality, the weight of the shotcrete layer can pull out loose rock and fall from the tunnel profile. The early strength of shotcrete is often tested to establish a re-entry criterion for the crew to work underneath fresh shotcrete.

For underground rehabilitation/repair projects, in-place bond strength shall be tested as per project specification. Tests can be conducted either at mockup, initial construction stage, or during construction (Radomski et al. 2019).

15.3—Required personal safety equipment

Proper clothing should include steel-toed boots, hardhats, gloves, long-sleeved shirts and pants, safety glasses, and hearing protection for all members of the shotcrete crew as well as all other workers, inspectors, engineers, and visitors to the job site; reflective strips should be used on clothing. In special cases, visitors may not be required to wear gloves if their exposure to hazards is low. Long-sleeved shirts and pants are highly recommended for the shotcrete crew.

Rubber gloves should be made available and used when handling cement, liquid accelerators, or admixtures.

The use of safety glasses or other eye protection by the shotcrete crew and all job site visitors is mandatory. Cement particles and rebound can easily cause enough irritation or injury to the eyes that the affected person will have to immediately leave the job site for medical attention. The nozzleman is especially susceptible to problems of shotcrete materials in the eyes. An accidental direct spray of shotcrete into someone's face can cause permanent blindness. Eye wash stations should be available at the shotcrete site.

Disposable dust masks, half-face carbon filter masks, or respirators (positive-pressure breathing apparatus) should be used by workers handling cement, supplementary cementitious materials, and dry powdered accelerators, and half-face masks or respirators should always be used by the shotcrete crew, inspectors, and visitors during shotcrete placement. Figure 15.3a is a photograph of a shotcrete nozzleman wearing required safety equipment.

Special consideration should be given to the types of helmets that combine a hardhat with a face shield and fan blowing air through a filter and into the helmet/face shield unit. This puts filtered air in front of the user's face. The posi-

Fig. 15.3a—Shotcrete nozzleman with personal safety equipment.

Fig. 15.3b—Shotcrete nozzleman with safety helmet.

tive pressure from the fan keeps the dust from entering the area between the face shield and the user's face. Some types of helmets use a belt-mounted fan that blows filtered air to the helmet through a hose. Figure 15.3b is a photograph of a shotcrete nozzleman with a safety helmet. Other types of helmets incorporate the fan and filtering unit into the helmet with electrical power carried to the helmet-mounted fan via an electrical cord from a belt-mounted rechargeable battery pack. Although somewhat costly to purchase and maintain, this type of filtering helmet is vastly superior to a hardhat, safety glasses, and respirator.

For some helmet units, layers of peel-off transparent covers for the face shields are available. When the top layer of a face shield cover becomes scratched or dirty, it can be peeled off, exposing a new, clean, unscratched layer. Hardened face shields are also available for some units. The hardened face shields appear to be superior to the peel-off layer types.

Fall protection is another evolving area of job-site safety, and procedures and equipment that have historically met standardized requirements may no longer be acceptable. It is therefore essential that job-specific fall protection procedures and equipment be developed consistent with current requirements and codes (for example, OSHA 29 CFR 1910 and 29 CFR 1926). Training is an essential element of any program, as noted elsewhere in this document. Special attention should be paid to additional state and local safety requirements.

15.4—View of shotcrete work

Good lighting is neither expensive nor difficult to achieve. Light stands with halogen or LED lamps can be easily fabricated and connected to an available electrical system or run off a small, portable, air-powered generator. In addition, adjustable halogen lights can be mounted on mobile shotcrete equipment and vehicles. A good lighting system improves line-of-sight communication and improves the quality of the shotcrete application by making hazardous ground conditions more visible. Figure 15.4 is a photograph of a well-lighted tunnel heading.

Fig. 15.4—A well-lighted tunnel heading.

Good ventilation is important; it removes dust and mist created by the shotcreting process, enabling the nozzleman and the rest of the crew to better see the nozzle, the surface being shotcreted, the rebound, and other personnel in the immediate area.

A supply of water and cloth rags or towels for cleaning safety glasses and face shields is recommended, as are backup safety glasses and face shields. Water for washing eye protection devices is usually available because most projects have air and water utility lines. These, however, may be under high pressure. Keeping a clean supply of towels can be difficult in underground operations because there is usually dirt everywhere, and various objects are commonly stolen from equipment and job sites.

15.5—Communications

Line-of-sight contact between the nozzleman and the shotcrete machine operator should be maintained whenever possible. A system of hand or cap lamp signals is used to indicate specific operator or crew instructions. This system has evolved and is used by the industry to overcome communication difficulties experienced underground.

Helmet-mounted, two-way radio systems are also an effective and preferred method of communication. Low-cost units available at local electronic stores are usually an economical solution. Two-way radio communication, however, has been found to be less important if the nozzleman has complete control of the water and the ability to turn the shotcrete machine on and off as required. These controls can be built into the remote controls of shotcrete booms, or robots if an electric-powered shotcrete machine is used.

Mine and tunnel telephone systems should be in place before the start of underground shotcreting operations. Should an injury occur that requires immediate outside assistance, mine telephones enable a considerable amount of time to be saved. Mine telephones partially covered with reflective adhesive tape are more visible and are quickly identifiable in an emergency.

Plugged shotcrete lines are a frequent hazard in underground applications that can, in a worst case, lead to bursting shotcrete lines and uncontrolled spreading of shotcrete at high velocity. It is important to communicate and make

other staff, inspectors, and visitors in the area aware about the potential hazard.

15.6—Nonpersonal safety equipment

Whip checks or safety chains should be used to tie down the ends of all compressed air hoses. Hoses that come unattached and are free to whip around as compressed air is discharged can be deadly.

Fire extinguishers of a suitable size should be available on or close to the equipment. Fire extinguishers partially covered with reflective adhesive tape are more visible and quickly identifiable in an emergency.

15.7—Recommended specifications

Recommended specifications for safety are provided in Table 15.7. 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. The MSHA and OSHA (construction as well as general industry) contain specific requirements for underground safety that are beyond the scope of this checklist. The specifier should be familiar with these and ensure they are addressed.

Table 15.7—Example guide specification for safety

Section/ Part/Article	Recommended specification language	Notes to the Specifier
15.1	The contractor shall prepare and submit a safety plan addressing all potential hazards to be encountered on the job site.	Refer to Section 15.2.
15.2	The contractor shall supply personal safety equipment for all personnel involved with shotcrete, both underground and at the surface. Submittals shall be in accordance with Example Specification Section 3.1.8.	Refer to Sections 15.3 and 15.6.
15.3	The contractor shall provide a well-lighted and ventilated work area for shotcrete application. Submittals shall be in accordance with Example Specification Section 3.1.8.	Refer to Section 15.4.
15.4	The contractor shall provide an adequate and safe means of communication between all members of the shotcrete crew.	Refer to Section 15.5.
15.5	The contractor shall devise and implement an escape plan consistent with the owner's requirements.	Escape plans should be devised before the commencement of any shotcreting work. A quick and safe exit is imperative to the safety of workers and visitors. Escape plans should be discussed with all workers and visitors. These plans should be posted in the project surface operations office and underground near the job site.
15.6	The contractor shall provide re-entry criteria allowing staff to re-enter into an area underneath freshly installed shotcrete.	Refer to Section 15.2. The re-entry criteria may need to be developed in cooperation with the designer, based on the weight/thickness of the green shotcrete, shape of the tunnel, and strength development.
15.7	The contractor shall provide and implement procedures for cleaning of concrete lines and removal of plugs, while protecting non-shotcrete crew personnel and visitors.	Refer to Sections 15.5 and 15.6.
15.8	In areas where existing permanent tunnel ventilation systems are in use for active portions of the system, the work area shall be isolated from the ventilation system to stop dust and other matter generated by the shotcreting process from entering the permanent tunnel ventilation system, or wet process shotcrete shall be used.	
15.9	Protect drains to prevent effluent from entering drains. Collect all waste concrete and wash and dispose of in accordance with all laws and regulations.	

CHAPTER 16—PREPARATION FOR SHOTCRETING AND GROUNDWATER CONTROL

16.1—General

The bond interface between shotcrete and rock has long been recognized as critical to the performance of shotcrete used for ground support. Although bond properties are not typically accounted for quantitatively in ground support design, the effectiveness of shotcrete, either as a structural support or as a sealant, is influenced by the effectiveness of the bond between the shotcrete and the rock or soil substrate. For this reason, wash-down, blow-down, and/or other surface preparation procedures before shotcrete application are typically imposed by specification and are subject to inspection in most tunnel QA/QC programs.

16.2—Factors affecting shotcrete adhesion and bonding

Surface preparation is important for achieving adequate shotcrete bond. Inadequate preparation can result in little or no bonding in the worst of naturally occurring conditions. Factors that can inhibit or reduce the development of adequate bond are described in this section.

Surface laitance, dust, and other impurities, which can be expected in both drill-and-blast or mechanically excavated openings, can lead to poor bonding if not removed before shotcrete application. Dust often results from the blasting process, which produces fine-grain particles that adhere to the profile of the excavated openings. General construction activities and the shotcrete operation itself are other sources of dust. If not removed during surface preparation, these particles act as an interfering layer or laitance and can cause the initial layer of shotcrete to spall or slough from the profile during application. Cleaning is therefore necessary before each successive layer of shotcrete is applied.

In most instances, high-pressure air washing, water washing, or both, is sufficient. In some special geological cases, such as raveling conditions or low-cohesion soft ground, aggressive pretreatment can be detrimental. Substrate types that result in lower bond strength, or no measurable bond strength at all, include weathered, geologically altered, or soft friable rock; highly mineralized materials; soft, slippery coatings on joint surfaces; raveling ground behavior; or low-cohesion soft ground. Where these conditions occur in proximity to faults or intensely fractured rock, establishing immediate and effective ground support is made difficult by spalling, sloughing, and debonding shotcrete. The normal requirement for surface preparation may have to be curtailed because the effects of exposure to air and water can cause rapid deterioration of the profile that leads to opening instability that may place personnel at risk. If such conditions are encountered, surface preparation requirements should be adjusted to avoid unnecessary exposure of construction personnel to hazards. In these conditions, time is typically of the essence and an immediate installation of shotcrete after excavation or even during excavation (pocket excavation) is required.

Certain coal-measure rocks; weathered, friable shale; and soft mudstone can be difficult to bond to because of their weak and friable nature. When these materials show a tendency to develop swelling pressures, the effects of debonding are further exacerbated. In hard rock, the presence of clay or micaceous materials, talc, and pyritic or chlorite minerals may result in minimal bonding. Naturally occurring oils and hydrocarbons associated with carboniferous deposits and oil shale can, in sufficient concentrations, act as debonding agents and make shotcrete application difficult. Some types of rock, such as chalk, some dolomites, serpentinite schists, cretaceous shales, and kimberlite ores, may soften or slake when exposed to air and water, causing shotcrete to spall and slough during application. Such materials may require pretreatment with surficial sealants such as sodium silicate to facilitate shotcrete application and the development of adequate bonding. In extremely weak sandstones and mudstones or in soft ground, the weight of shotcrete may overcome the apparent cohesion of the surface coating and induce failure before the shotcrete has achieved final set. The use of water and compressed air during washdown and surface preparation can have the same detrimental effect on poorly cemented, low-cohesion materials. Brecciated, loose, or gravel-like materials can impose similar problems during shotcrete application.

Poor curing practice (refer to Chapter 19), lack of protection for freshly-placed concrete, or over-accelerated shotcrete can result in undesirable shotcrete shrinkage and lead to debonding. Thin sealing coats of shotcrete are particularly susceptible to separation from the rock. Groundwater can also be problematic if water pressure is permitted to build up behind freshly applied shotcrete. The use of accelerating admixtures can also add to this problem by causing increased shrinkage, leading to separation between the shotcrete and ground surface. Alternative methods, such as embedded channel sections and pipes, can relieve water pressure while channeling and controlling water inflow sufficiently to allow shotcrete application.

Remedial mining or tunnel restoration projects can impose unique surface preparation requirements. In some mining operations, where mineral extraction has previously taken place above development levels, mud, water, and other mining related by-products such as dust suppression emulsions and diesel particulates, can seep into the lower development areas. These materials carried in solution or suspension can cause localized bonding problems when encountered in development openings. In road and railroad tunnels, buildup of soot from diesel emissions may require sandblasting to provide a sufficiently clean surface on which to bond remedial shotcrete. Underground structures that have been fire-damaged require careful remediation, including removal of fire-damaged concrete, shotcrete, grout, or rock to expose a clean, intact surface before the application of remedial shotcrete.

Vibrations from adjacent mining or development operations can cause freshly applied shotcrete to separate or spall. In drill and blast excavation, the subsequent blast round may destroy shotcrete placed up to the face of the opening.

Damaged and debonded shotcrete should be removed by scaling until intact material is encountered. Subsequent shotcrete should be used to bond the adjoining layers together and to establish integral support. Where multiple shotcrete applications are used to install a thick lining, the surface of the previous layer of shotcrete should be cleaned. This will remove the laitance and provide a substantial bond between layers. Where carbonation has occurred, surfaces should be scoured with compressed air and water before shotcrete application.

Extremes in temperature can exist for a surprising distance into the tunnel. This is a special problem for remedial work in existing tunnels with natural airflow. In cold condition applications, surface water and groundwater can freeze. All observable ice should be removed before shotcrete placement. Freezing of surface water can cause spalling or weaken the shotcrete bond.

Where groundwater is encountered in underground construction, appropriate groundwater control and handling procedures should be employed as described in Section 16.4. Shotcrete application can become difficult and time-consuming where widespread seepage and flow is encountered. Washdown (where permitted by rock type) and surface preparation is still important in promoting adhesion and the development of adequate bonding. Nevertheless, shotcrete should not be applied to wet surfaces (unless it is unavoidable), as water on the surface creates a high water-cementitious materials ratio (*w/cm*) at the critical bond interface, thereby reducing bond strength.

16.3—Surface preparation

At the end of the excavation phase of the underground construction cycle, the tunnel profile is inspected and the surface prepared. Immediately before shotcrete application, the profile of the tunnel is cleaned with compressed air, water, or both, using the shotcrete nozzle, blowpipes, or ancillary air-water jet. Additional hand scaling may be done as determined by the construction crew. Only when the surface of the opening profile has been prepared can shotcrete application be initiated. Immediately before shotcrete application, the surface that is about to receive the shotcrete should be clean and damp, a condition best described as saturated surface-dry (SSD). This permits the shotcrete applied to the excavated profile to adhere and, in the course of achieving initial and then final set, remain bonded to the ground. Both the shotcrete strength and the bond are limited and fragile, particularly at early ages. The weight of the shotcrete, vibration, or disturbance can be sufficient to cause the shotcrete to fall or partially separate from the rock. In this case, the bond may be reduced or eliminated.

Debonding can be identified after hardening by a dull or drummy sound when the shotcrete is hit with a hammer or bar. The performance of the shotcrete can be significantly reduced when debonding occurs. Thin sections of shotcrete are subject to localized bending moments and can become the focal point of stresses and cracking, all of which indicate that the debonded shotcrete is only partially effective as a ground support system.

16.4—Groundwater

The presence of large volumes of water or water at high pressures generally precludes the use of shotcrete unless specific measures are used to dewater or precondition the ground using grouting or other measures. If groundwater control is carefully factored into the design and effectively implemented during construction, shotcrete application only needs to consider low to moderate water inflows at low pressures. This may still result in localized areas that are difficult to shotcrete and in the need to implement specific temporary measures to control, handle, and dispose of groundwater.

Shotcrete can be applied in conditions where groundwater is encountered, but doing so may require skillful adjustments by the nozzleman. The extent of these adjustments depends on the nature of groundwater inflow. If specific measures are prescribed by specification and include the use of embedded drainage channels, pipes, or hoses, then these approaches should be employed. If groundwater is incidental in nature, ranging from general weeping to damp surfaces, reducing nozzle water and increasing accelerator dosage in dry-mix shotcrete or increasing accelerator dosage in wet-mix shotcrete may address the condition.

Shotcrete should not be placed on surfaces with flowing groundwater because its adhesion to the substrate surface will be impaired. If a moderate volume of water is flowing from a fissure or joint, the best approach is usually to systematically shotcrete around the flow to confine the water to single point source while allowing the peripheral shotcrete to achieve final set. A short hole should then be drilled into the single source flow to a depth of 2 to 3 ft (0.67 to 1 m). A preassembled pipe and valve are then inserted into the hole. The valve on the free end of the pipe should be left fully open to allow the water buildup to flow through the pipe. The pipe should be shotcreted and may require the use of accelerated shotcrete. The secured pipe allows the water that has accumulated behind the shotcrete to flow without building up adverse hydrostatic pressure. This pipe can later be closed and intermittently opened to relieve the buildup of water pressure until shotcrete application is complete, at which time grout can be injected and the pipe can be cut off.

Several basic elements of shotcrete application in wet ground should always be considered. Avoid trapping water behind the shotcrete lining because water pressure will build up that can be strong enough to cause a failure of the lining. Surficial moisture or surface water should be confined to a single point as previously described. Water should be worked to the lowest point, if possible, for collection in a groundwater control system (for example, invert channel or temporary sump). If shotcrete is used as temporary ground support in shaft construction, water should be channeled, controlled, and drained to avoid the increased buildup of hydrostatic pressure at a lower level due to migration behind the shotcrete lining or shaft wall.

Where the treatment described does not control the water, grouting methods should be considered before ground conditions become significant problems.

16.5—Recommended specifications

Recommended specifications for surface preparation are provided in Table 16.5. 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 16.5—Example guide specification for surface preparation

Section/Part/ Article	Recommended specification language	Notes to the Specifier
16.1	Surface preparation	Consideration should be paid to the overall design of the shotcrete support system as well as the more general aspects of surface preparation. Some general guidelines in this area are provided in Section 16.1; however, these Notes to Specifier are not intended as a design guide.
16.1.1	Prepare surfaces to receive shotcrete to meet specified bond strength, giving proper consideration to the geological, geotechnical, and hydrogeological conditions.	
16.1.2	To prevent excessive absorption by the ground surface of the mixing water from the shotcrete, pre-wetting of the ground surface by spraying with clean water prior to applying the shotcrete is permitted. Pre-wetting is prohibited or shall be stopped immediately if the stability of the ground surface is disturbed. The amount of pre-wetting will be dependent upon the absorption qualities of the ground. Puddling, ponding, or leaving freestanding water shall be avoided. The ground should be conditioned to a saturated surface-dry (SSD) condition prior to shotcrete application.	
16.1.2	If shotcrete is applied in several layers, pre-dampen the receiving surface.	
16.1.3	Before shotcrete is applied over steel surfaces, all debris, shotcrete, loose mill scale, rust, oil, paint, or other contaminants shall be removed by sandblasting or other methods approved by the engineer.	
16.1.4	Where shotcrete is to be used for repairing deteriorated concrete, all spalled, severely cracked, deteriorated, loose and unsound concrete shall be removed by chipping, scarifying, abrasive blasting, water blasting, or other mechanical method approved by the engineer. Abrupt changes in the repair thickness shall be avoided. The perimeter of the repair shall be saw cut to a depth compatible with the type of repair, but not deeper than the concrete cover over reinforcement. If saw cutting is impractical, the edges are to be chipped with a slight taper. Feather edging is not permitted.	
16.1.5	Where shotcrete is to be placed against a smooth concrete surface, the surface shall be roughened by sandblasting, bush hammering, or other suitable mechanical means as approved by the engineer.	
16.1.6	When surface preparation is completed for repair applications, all repair areas shall be thoroughly cleaned by sandblasting, water blasting, or other methods to remove any trace of dirt, grease, oil, and other substances that could interfere with the bond of newly placed shotcrete. All freestanding water shall be blown away by compressed air.	
16.1.7	Porous surfaces in a repair application shall be kept damp for several hours before shotcrete is applied.	
16.2	*Drainage*	
16.2.1	Drainage materials used to control groundwater in shotcreted areas shall be of the type specified in the contract documents.	
16.2.2	Alternative means of groundwater control may be submitted by the contractor for review and acceptance by the owner.	

CHAPTER 17—GROUND REINFORCEMENT INSTALLATION

17.1—General

Effective installation of ground support requires that appropriate ground support elements are installed as specified, in locations identified in the project drawings, or as dictated by the conditions encountered during construction. The subsequent location and installation of ground support largely depends on the care and control achieved during the excavation phase. Shotcrete tolerances should reflect the effects of the excavation, required thickness, and finish required during application. Rock bolt locations, spacing, and orientation are also influenced by the process of excavation and the consistency of the opening profile. The performance of steel sets or lattice girders is influenced by over-excavation and profile irregularities. Reduced contact between the excavated profile and the steel set or lattice girder may require additional shotcrete or alternatively blocking or cribbing, which may not be desirable (refer to Chapter 5).

Composite lining systems can combine plain or fiber-reinforced shotcrete, rock bolts, welded wire or steel reinforcement, and possibly, when needed in soft ground, lattice girders, or steel sets. The specific combinations, sequence, and timing of ground support elements and their installation are usually established by the design engineer and safely implemented by the contractor. These factors can affect the short-term stability and long-term performance of the opening and, in soft ground, surface settlements, and are therefore the subject of QA/QC inspection, documentation, and record keeping as described in Chapter 9.

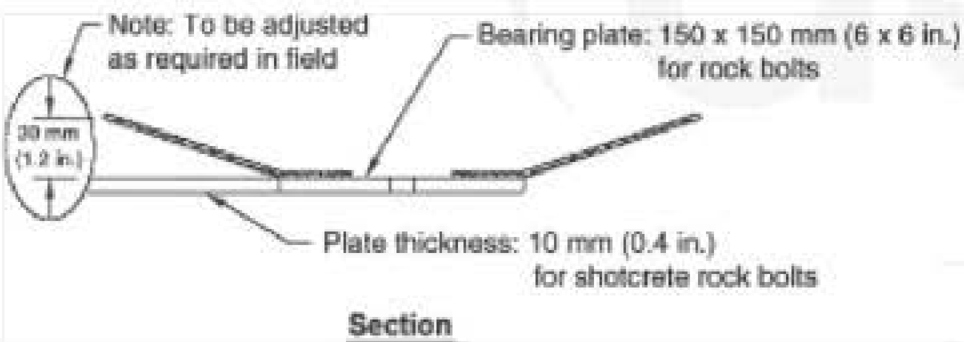

Fig. 17.2a—Rock bolt anchor plates with reinforcing bar "wings."

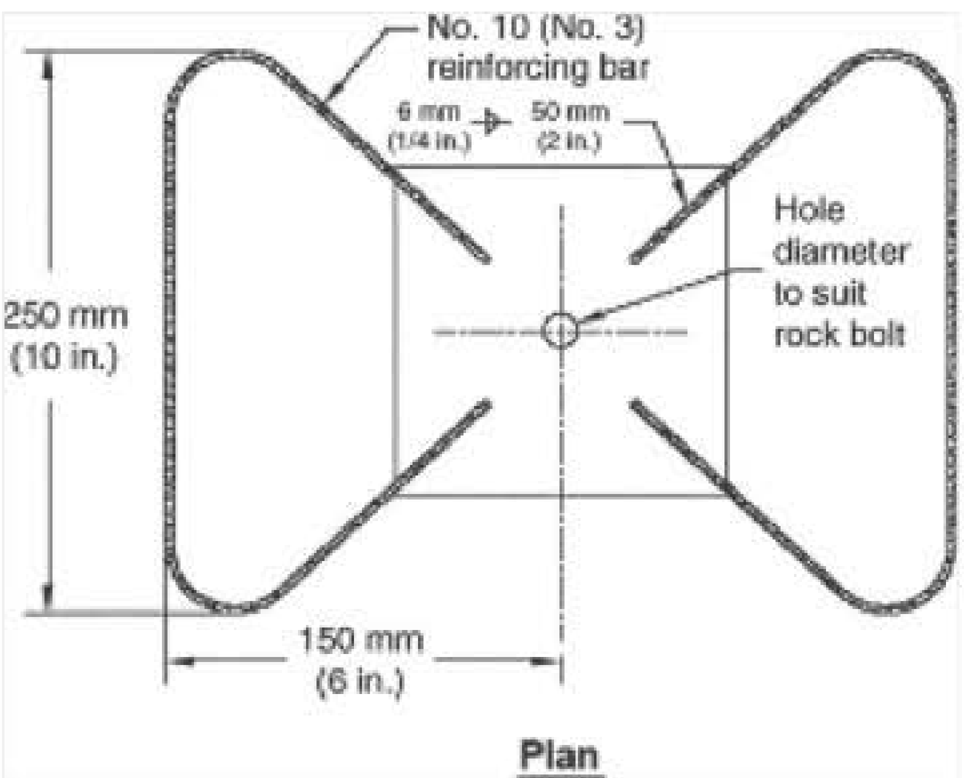

Fig. 17.2b—Rock bolt anchor plates with reinforcing bar "wings."

17.2—Rock bolt installation

Numerous types of proprietary rock-reinforcement systems are currently available as ground support. The most common categories include rock bolts grouted with cementitious and epoxy resin, mechanical bolts with end anchors, and cables. Each of these systems has recognized attributes and deficiencies; no single system is optimal in terms of performance and cost for all conditions. Figures 17.2a and 17.2b illustrate a rock bolt plate that enhances interaction between the rock bolt and the shotcrete layers.

The engineer should decide whether shotcrete should be installed before or after the installation of the rock-reinforcement system regardless of the system used. In certain circumstances (for example, raveling ground), shotcrete may be applied before muck removal to seal the rock against deterioration and to provide early initial support for safety. Bolts would then be installed in holes drilled through the shotcrete. Worker safety is an important consideration in shotcrete timing. Robotic shotcrete arms, however, allow shotcrete placement in advance of the installation of the rock-reinforcement system without exposing the nozzlemen.

17.3—Steel set installation

Steel sets can be installed in partial headings with benches or full face openings and in sections or assembled. To avoid having tights in the tunnel profile and provide adequate space for installation, excavation needs to be large enough to provide sufficient clearance. This permits the steel sets to be erected, but also leaves an aperture between the shotcrete or rock profile.

To secure the steel set, blocking is usually required and, as previously indicated, the extent of blocking influences the performance and support contribution provided by the steel set. If shotcrete is used as blocking, difficulties arise when trying to place the shotcrete in the space between the steel set and the rock. If the tolerance is tight, it is nearly impossible to completely fill the aperture while avoiding the inclusion of rebound. A greater distance between the steel set and the rock makes shooting the shotcrete blocking easier, but may lead to a substantial increase in the volume of shotcrete required as blocking and lagging between steel sets. Excellent excavation and ground support installation control within proper tolerance is necessary to minimize these problems.

17.4—Lattice girder installation

Lattice girders are frequently used in tunneling applications, where the lattice girder is fully embedded and becomes part of the initial shotcrete lining. The use of lattice girders can mitigate several installation problems associated with steel set installation. Although they have limited structural capacity, lattice girders can, when combined with shotcrete, increase the support capacity, especially during the period following excavation. Lattice girders provide immediate

Table 17.6—Example guide specification for reinforcement placement

Section/Part/ Article	Recommended specification language	Notes to the Specifier
17.1	*Reinforcement*	
17.1.1	Reinforcement materials used in conjunction with shotcrete shall be of the type specified in the contract documents.	A change in ground conditions may result in a reinforcement change. The range of tunneling conditions anticipated is usually established in the geotechnical baseline report for the project.
17.1.2	The layout and fastening of reinforcement shall be as detailed on the project drawings and specified in the contract documents.	

support for the ground before the shotcrete gains its strength. The advantage of the lattice girder system is that the lattice girders are relatively easy to install. Shotcrete can be applied through the lattice structure and effectively envelope the lattice bars without trapping rebound or leaving voids, provided that the nozzleman is both experienced and skilled.

17.5—Face support

Especially in soft ground, face stability may be an issue and require face support. Face support can include an unexcavated portion of the ground (face wedge), face bolts with or without mesh, or a combination of the two. Often, these measures are combined with shotcrete to either seal the ground surface or create structural members supporting the face.

In weak ground conditions, face-sealing shotcrete is applied as a systematic support measure. Similarly, face wedges are also frequently sealed with shotcrete to avoid deterioration. If face bolts are used, typically relatively long bolts are installed to provide face support for several excavation rounds before another set of face bolts must be installed. Often, fiberglass bolts are used because they tend to break during excavation without negatively impacting the integrity of the ground. For longer stoppages, thicker shotcrete is typically installed in a dome shape to support the face and may be anchored by face bolts.

Because excavation typically continues, all face support measures will be subsequently demolished during the process. Fiber-reinforced shotcrete is therefore advantageous versus shotcrete reinforced with mesh.

17.6—Recommended specifications

Recommended specifications for reinforcement placement are provided in Table 17.6. 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 18—SHOTCRETE APPLICATION

18.1—Methods used to control thickness

Several methods are available for use in controlling the thickness of shotcrete applied to the wall of a tunnel or underground opening:

(a) Nails or pins may be installed either intermittently or in set patterns to ensure a minimum thickness. The shotcrete is applied until the nails are covered. In a large underground opening, an operator may have difficulty seeing the nails or pins while shotcrete is being applied, and the nails can be inspected after the shotcrete is in place; when welded wire reinforcement or reinforcing steel is attached to the tunnel wall as part of the lining, it may serve as a thickness control guide. The shotcrete operator can observe when the welded wire reinforcement or steel is covered. Guide pins serve to verify the proper thickness of cover over welded wire reinforcement installations. The welded wire reinforcement should have openings large enough to ensure that the shotcrete envelops the welded wire reinforcement and is not impeded as the applied layer bonds to the wall or surrounds any reinforcement. Lattice girders or steel sets provide an indication of alignment and minimum thickness, but these elements also require guide pins to ensure the proper thickness of cover.

(b) High tensile wire may be used when a final thickness is required to a fine tolerance. The gauge wire method usually involves overshooting the thickness and cutting or trimming back the fresh shotcrete to the wires with a straightedge (also called a cutting rod).

(c) The final shotcrete thickness may be verified by using a template to identify any under- or over-thickness areas for correction.

(d) Final shotcrete tolerances can also be verified using surveying techniques. Photographic survey and three-dimensional laser systems can also be used for rapid profile assessments. Thermographic or infrared techniques can be used to identify areas where groundwater seeps through the liner.

(e) Electronic survey systems with real-time feedback to the shotcrete crew.

18.2—Cover, alignment, and tolerance

The coverage, alignment, and dimensional tolerance of the applied shotcrete are important to performance of the tunnel support structure. The coverage may be estimated by calculating the yield of the shotcrete applied. The surface area of the tunnel shotcreted divided into the volume of shotcrete placed, less waste and rebound, gives a nominal thickness for the coverage. In drill-and-blasted excavation, the coverage should be 150 to 200% of the design thickness to account for overbreak and surface irregularities. In mechanically excavated tunnels, the yield more closely reflects the actual shotcrete placed.

The tolerance requirements for thickness, alignment, and finish should meet the final design and performance requirements as specified and be economically feasible. If required, shotcrete can be placed and finished to the same tolerances as formed concrete. The cost of this finished shotcrete lining is much higher than for a hand-held or a robotic nozzle

finish. A close tolerance finish requires the installation of shooting wires on a maximum spacing of 3 ft (1 m), cutting the shotcrete back to the wires, and finishing by a crew of finishers. In many cases, a close tolerance shotcrete lining is not required. Shotcrete applied to a minimum thickness and nozzle finish is generally acceptable for most underground structures supported by composite lining systems.

18.3—Recommended specifications

Recommended specifications for shotcrete application are provided in Table 18.3. 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.

Table 18.3—Example guide specification for shotcrete application

Section/Part/Article	Recommended specification language	Notes to the Specifier
18.1	*Shotcrete application*	
18.1.1	Shotcrete shall be applied in accordance with good practice as outlined in ACI 506R.	Both dry and wet methods are employed for ground-support applications. Skilled, experienced, well-trained crew members are essential to successful applications. Although certain techniques are specific to each method, the nozzleman requirements for proper application are well described in ACI 506R and should be followed as a basic requirement of all underground shotcrete operations. For an additional reference, refer to ACI CCS-4.
18.1.2	Shotcrete application employing additives such as silica fume and accelerating admixtures shall comply with manufacturers' recommendations for proper practice.	
18.1.3	Precautions shall be taken to prevent overspray, rebound, or waste from being incorporated into the work area.	
18.1.4	Areas adjacent to the receiving surface and substrate shall be maintained in a clean and SSD condition until shotcrete is applied.	
18.1.5	Adequate ventilation and lighting shall be provided to the work area to ensure good visibility. Precautions shall be taken to prevent unusual airflow, wind, or water from influencing the quality of work at the substrate, material spray, or finished surface.	
18.1.6	Safe and adequate working platforms or mechanical nozzle manipulators shall be employed to access the work area in a manner that provides proper nozzle distance and angle of incidence at all times.	With the dry-mix shotcrete process, material is transported through the delivery hose in an air stream, and manual nozzle control is acceptable, though modern robotic equipment is preferable for safety reasons. Wet-mix shotcrete application often employs concrete pumps with output capacity beyond a person's ability to support a nozzle system comfortably and safely. Modern wet-mix ground support applications typically employ mechanical means to hold and manipulate the nozzle. Robotic units are best operated by skilled nozzlemen with relevant training and experience in manual shotcrete application.
18.1.7	Excess materials shall be trimmed, cut, or removed from the application area and be properly disposed of in accordance to project requirements.	
18.1.8	The contractor shall clean and maintain all shotcrete and ancillary equipment.	
18.1.9	Air and substrata temperatures shall be maintained at 40°F (4.4°C) or higher during shotcreting. Shotcrete temperature shall be maintained at 50°F (10°C) or higher for a minimum of 7 days following shotcreting or compressive strength exceeding 70% of the design strength. The layout and fastening of reinforcement shall be as detailed in the contract documents. Reinforcement shall not be loose or vibrating during the shotcreting. When water is encountered, suitable means, such as the use of drainpipes, shall be employed to direct the water away from the area to be shotcreted.	
18.1.10	Shotcrete mixture temperature as placed must be maintained at 55°F (12.8°C) or higher. Adjustments to the mixture design including the use of a non-chloride-containing accelerator may be used to meet strength requirements during cold weather.	
18.1.11	Shotcrete shall not be placed on any frozen or spongy surface or where freestanding, ponding, flowing, or dripping water exists.	For ground freezing, refer to Section 19.2.
18.1.12	Shotcreting shall be suspended if high air flow prevents proper application procedures, temperature approaches freezing and the shotcrete cannot be protected, or water causes wash out of the fresh shotcrete.	

Table 18.3, cont.—Example guide specification for shotcrete application

18.1.13	Shotcrete application shall be made from an angle as near perpendicular to the surface as practical with the nozzle held approximately 2 to 6 ft (0.6 to 1.2 m) from the work. In all cases, shotcrete shall be built up to required thickness by making several passes of the rotating nozzle over a section of the work area. Shotcrete shall be applied from the bottom and proceeding to the top of the work area on vertical surfaces. Defects such as slugs, sand spots, or wet sloughs shall be cut out and replaced after initial set but before final set.	
18.1.14	Special attention shall be given to encase reinforcing bars, steel sets, and lattice girders. The nozzle shall be held closer than normal and at a slight upward or sideward angle to permit better encasement. In addition, the mixture shall be sufficiently flowable to force the shotcrete behind the bar or steel set.	
18.1.15	The layout and fastening of reinforcement shall be as detailed in the contract documents. Reinforcement shall not be loose or vibrating during the shotcreting.	
18.1.16	Construction joints or end of workday joints shall be angled off to a thin, clean, regular edge, preferably at a 45-degree angle. The entire joint shall be thoroughly cleaned and wetted to SSD condition prior to application of adjoining shotcrete.	
18.1.17	Shotcrete shall be applied in layers or in a single thickness, depending on the position of the work. Overhead and vertical work shall be shotcreted in layers just thick enough to prevent sagging or dropouts, usually 1 to 2 in. (25 to 50 mm) at a time. Where a layer of shotcrete is to be covered by a succeeding layer, it shall be roughened before setting. All loose, uneven, or excess material, glaze, and rebound on a receiving substrate shall be removed by brooming, scraping, sand blasting or water blasting, or other means acceptable to the engineer and the surface cleaned and brought to SSD condition before placing subsequent layer of shotcrete. Curing compound or other bond-breaking materials shall not be applied to surfaces that will be covered by an additional layer of shotcrete.	
18.1.18	Rebound shall not be salvaged or reused in the work but shall be collected and disposed of by the end of the work shift in which it was created.	
18.1.19	Use blowpipes or similar means to avoid overspray of rebound, especially while shotcreting at or close to the invert.	
18.2	*Thickness control*	
18.2.1	Shotcrete shall be placed to the thickness and tolerance shown on the project drawings and cited in the contract specifications.	A minimum shotcrete thickness is usually necessary to provide an integral ground support system. A minimum thickness may also be required to protect the reinforcing steel or other support steel from corrosion or from abrasion (for example, in water tunnels) or to serve as fire protection.
18.2.2	The nozzleman and crew shall provide sufficient and acceptable control system to provide proper thickness and grade. Use adequate ground wires, pins, nails, or other accepted means to establish the thickness, surface planes, and finish lines of the shotcrete.	
18.2.3	Shotcrete thickness for any single layer shall be limited to avoid debonding or sloughing.	The maximum thickness applied is also important so that the shotcrete lining does not infringe on the tunnel design envelope.
		Refer to Section 18.1 for further discussion of thickness control.
18.3	*Surface finish*	
18.3.1	No surface finishing work shall be allowed if the ground support is not properly supported by older shotcrete that has gained sufficient strength and, if finished overhead, the freshly applied shotcrete layer is thicker than 2 in. (50 mm).	
18.3.2	The surface of shotcrete initial linings for ground support shall not receive a special finish during the excavation and support.	The gun finish, a textured, uneven surface, is the natural finish left by the nozzle after the shotcrete is brought to approximate line and grade.

Table 18.3, cont.—Example guide specification for shotcrete application

18.3.3	If a waterproofing membrane is installed on top of the shotcrete initial lining, apply a smoothing shotcrete layer as required to achieve smoothness criteria prior to waterproofing installation. Meet substrate requirements of the waterproofing membranes installer. The depth-to-distance ratio between two crests (wavelength) as measured with a 10 ft (3 m) straightedge in random direction to be one-fifth or less or as required per contract documents. Cut off and patch projecting portions of any support elements flush with the face of the shotcrete surface and remove temporary supports and hangers installed in shotcrete for construction process. Ensure that embedded elements of the shotcrete lining are covered by at least 1 in. (25 mm) of plain shotcrete prior to installing the waterproofing membrane system. Repair damaged or spalled surfaces, voids, and cracks having depths greater than 1 in. (25 mm) with shotcrete, quick-set grout, mortar, or equal. Ensure that surfaces are free of oils, grease, and gasolines, and remove loose soil and debris.	
18.3.4	If a better alignment, appearance, or smoothness is needed—that is, for a repair application or substrate for a waterproofing membrane—the shotcrete shall be placed a fraction beyond guide strips, ground wires, or other guides. It shall be allowed to stiffen to the point where the surface will not pull or crack when screeded with a rod or trowel. Excess material shall be trimmed, sliced, or scraped to true line and grade. The guide strips, pins, or ground wires shall be removed, and impressions removed, by floating.	
18.3.5	For shotcrete final linings, the use of accelerator shall be avoided or limited. The surface shall receive a wood float finish or natural gun finish, as indicated in the contract documents.	

CHAPTER 19—CURING AND PROTECTION

19.1—General

To a significant extent, the strength development of shotcrete applied in underground construction is determined by the subsurface environment and the efforts made shortly after shotcrete placement to facilitate and complete curing. Underground environments can provide beneficial curing conditions. Temperatures and relative humidity are generally more consistent than those experienced by surface structures, and extreme conditions are moderated. In deep mines or in regions with high geothermal gradients, rock temperatures can be high. This does not, however, eliminate the need for curing and protection of freshly placed shotcrete.

Mining and tunnel ventilation systems or the natural air flow after breakthrough have a considerable capacity to remove water from the surface of hydrating shotcrete through evaporation. Failure to complete hydration can result in surface or plastic shrinkage cracking and reduced strength. Specific measures that can be taken are to wet-down the surface of maturing shotcrete periodically to maintain a moist surface condition, and to install brattice curtains or misters to fog the environment. The provisions for curing shotcrete should be consistently and systematically implemented to achieve consistent-strength shotcrete and minimize potential cracks.

19.2—Protection

Shotcrete should not be allowed to freeze until it has reached a minimum compressive strength. Such conditions may occur at portal or shaft collar structures during winter or cold periods. A shotcrete that reaches 500 psi (3.5 MPa) before freezing takes place will not be damaged by freezing in one freezing-and-thawing cycle. Shotcrete temperatures should rise, however, above the freezing point to further develop strength. Even though shotcrete is known to develop greater heat of hydration than most concretes due to its higher cement content, it is generally placed in relatively thin layers that allow rapid loss of heat, partially counterbalancing the high heat-of-hydration benefit. In general, shotcreting operations should be stopped if the ambient temperature falls below 40°F (5°C).

In a hot-weather environment, the problems encountered with wet-mix shotcrete are the same as for conventional concrete: increased water demand, increased rate of slump loss, rapid setting, and difficulty in regulating the entrained air content. For dry-mix and wet-mix shotcrete, the finishing operations, if any, should proceed as rapidly as the shotcrete condition allows. Curing should also start as soon as possible.

19.3—Recommended specifications

Recommended specifications for curing and protection are provided in Table 19.3. 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.

Table 19.3—Example guide specification for curing and protection

Section/ Part/ Article	Recommended specification language	Notes to the Specifier
19.1	Curing	Curing is typically not required for shotcrete used as temporary support in a tunnel or shaft, but should be mandatory for final lining, rehabilitation, or repair projects.
19.1.1	After application, shotcrete shall be cured using a curing membrane, covering, water sprinkling, or misting. Membrane curing and covering must start soon after the shotcrete has been applied. Misting shall commence as soon as shotcreting is finished, but water sprinkling shall start only after the shotcrete has set.	The rough surface of the shotcrete natural finish usually requires more curing agent than is normally specified by the supplier (typically twice the recommended rate). Overhead surfaces may require even more curing agent because it is subject to dripping. Curing agent should be applied with equipment adequate to ensure sufficient velocity so that the product reaches the shotcrete surface, especially in overhead situations.
19.1.2	When a membrane-forming curing compound is used, it shall be applied at a rate meeting the moisture retention requirements of ASTM C309. Curing compounds shall be applied immediately after the shotcrete has been placed and finished in a manner that will not disrupt bonding to the substrata. Curing compounds shall generally not be applied to shotcrete where additional layers of shotcrete will be placed at a later date. Areas where additional shotcrete layers will be placed shall be cured with a curing membrane only if it has proven nondeleterious to bond or if it is properly removed by water jetting, sandblasting, or a similar process before the application of the next layer. When a latex material has been added to the shotcrete mixture, only a water-based curing compound shall be used. Rapid drying of shotcrete at the end of the curing period shall be avoided.	Curing agents usually impair the bond between shotcrete layers. For this reason, field tests should be carried out if the compound is to be left in place between layers. In all other cases, water jetting or sandblasting should be used to completely remove the product before applying a subsequent layer of shotcrete.
19.1.3	If no curing compound is used, shotcrete shall be cured by using one of the following materials or methods for a minimum of 3 days, until a subsequent layer of shotcrete is applied, or until specified strength is obtained: (1) Ponding or continuous sprinkling (2) Absorptive mat or fabric, sand, or other covering kept continuously wet (3) Vapor mist bath or continuous steam (not exceeding 150°F [65.6°C]).	
19.1.4	Natural curing is allowed only if the underground environmental conditions are satisfactory, such as when the relative humidity is above 85%.	In the case of natural curing, an 85% relative humidity condition is not by itself sufficient and may need to be augmented by spraying water on the finished shotcrete. Extremes of heat, cold, or excessive evaporation and dry-out due to airflow should always be avoided.
19.2	*Protection*	
19.2.1	Shotcrete shall be protected to maintain an internal temperature above 40°F (5°C) until the specified compressive strength is reached.	Refer to Section 19.1.
19.2.2	Before setting, shotcrete must be protected against running free water or any potential impact and vibrations.	Before setting, fresh shotcrete quality can be impaired if the shotcrete is vibrated, impacted, or moved. Finishing operations, if required, should be conducted by experienced finishers to prevent tearing or breaking of the shotcrete mass. Shotcrete in a developing drill and blast heading will always be subjected to vibrations from a subsequent round being excavated. Blast vibrations have little effect on previously applied, accelerated shotcrete, even, in some cases, right up to the face.

CHAPTER 20—SHOTCRETE FOR REPAIR AND REHABILITATION OF UNDERGROUND STRUCTURES

20.1—General

Underground structures are similar to surface infrastructure in that they require repair and rehabilitation to maintain them in a safe, functional, and economic condition. Modern urban environments, such as highway, mass transit, water supply, sewer, and railroad tunnels, are subject to varying degrees of deterioration over time. Concern for infrastructure has created an interest in the rehabilitation of existing underground structures. Many of the tunnels in North America were constructed during the first part of the last century and are approaching or have exceeded their anticipated design-life expectations. Due to the high cost of replacement, many tunnels are being rehabilitated to extend their useful life. Rehabilitation of underground structures is becoming common, and shotcrete is often the preferred repair method.

In subsurface mining, shafts, ramps, main access drifts, and a variety of secondary structures important to safe and productive mining operations are also subject to deterioration and require maintenance and repair due to mining activities. Unlike civil structures, the ground support used in permanent mine openings may include rock bolts, welded wire reinforcement, shotcrete, or steel sets, either individually or in combination. Deterioration of these support systems may range from bulging welded wire reinforcement loaded with raveled rock to partial collapse of the mine opening due to mining-induced seismic events (Kaiser et al. 2000).

Typically, the deterioration of tunnel and mine openings can be readily observed. Common indications of deterioration are cracking, displacement, discoloration, raveling, and spalling, which raise concerns during maintenance inspections that require further assessment and evaluation. For both civil and mining structures, careful assessment of the cause and effects of the deterioration are important as well as the original assumptions during the design—that is, groundwater drainage. Such assessment assists in establishment of the methods and means for rehabilitating the underground structure and in selecting the materials and installation methods for the repair to be completed safely and effectively.

20.2—Materials selection

Selection of shotcrete materials that meet all necessary properties established by the conditions and requirements can be difficult. Some require load-carrying capability and durability. Shotcrete used for defects deeper than 1.5 in. (40 mm) uses portland cement and well-proportioned fine aggregates. Durability can be enhanced by using special pozzolans, silica fume, or admixtures that reduce the permeability (Zhang et al. 2016). The use of site-batched or preblended bagged shotcrete requires special attention to shrinkage and curing. All shotcrete mixtures should be tested to select and confirm sufficiently low shrinkage properties.

Curing of shotcrete is critical in reducing early shrinkage and for future long-term performance. In structural applications, understanding the behavior of shotcrete in response to loads is important. Two important properties for load-sharing applications are the elastic modulus and creep. Whereas elastic modulus properties can be easily obtained, creep values are much more difficult to ascertain.

The use of shotcrete materials and additives that contain unknown ingredients or where new, unproven technology is being used should be avoided, except in experimental or pilot projects. Also, the combination of known additives and admixtures can lead to unexpected results and should therefore be tested prior to use.

The use of materials that contain gypsum results in uncontrolled expansion and extremely low durability when subjected to moisture. Some materials have been found to contain high amounts of alkali material that may result in early deterioration caused by alkali-silica reactions if the aggregates are reactive. Some materials are sensitive to

Table 20.2—Additives for dry-mix shotcrete

Additives	Benefit	Comments
Silica fume	Increased thickness; increased density; increased resistance to freezing and thawing; increased chemical resistance; reduced rebound; increased adhesion/bond; and increased flexural and compressive strength.	Accelerators may not be necessary if used.
Accelerators	Increased buildup of layers; reduced initial set time; and increased early strength gain.	Adverse effects: Increased drying shrinkage (critical especially for final linings, rehabilitation or repair projects); reduced 28-day shotcrete strength. Limited encapsulation of reinforcing bars or lattice girders elements if dosage and nozzle handling is not adapted.
Steel fiber	Eliminated shadows and voids that are created with conventional reinforcement; may replace awkward-, difficult-, and expensive-to-place welded wire reinforcement with improved quality control; improved impact resistance; and increased toughness (residual strength after cracking).	
Synthetic fibers	Microsynthetic fibers reduced plastic shrinkage cracking and improved spalling behavior during fires; and macrosynthetic fibers provide similar benefits to steel fibers.	At proper addition rates, macrosynthetic fibers provide similar toughness to steel fiber-reinforced shotcrete. Structural behavior of macrosynthetic fibers during tunnel fires (final lining applications) may be critical.

the methods of application. Latex modifiers have proven exceptional in overlays, but when used in some applications involving dry-mix shotcrete, have resulted in interlayer bond failure. Failure was caused by latex films forming on unfinished surfaces. The shotcrete process uses high-velocity air, which accelerates the formation of a bond-inhibiting latex film.

Polymer shotcrete is a special class of materials used to repair concrete surfaces. Epoxies and acrylics blended with graded aggregates produce strong and chemically resistant materials. They can be used for thin or thick applications where service or exposure conditions do not cause dimensional incompatibility problems. Polymer materials have a high thermal coefficient of expansion as compared with concrete. The use of such materials in confined underground environments requires serious consideration of potentially hazardous environmental, health, and safety conditions. Specific safety provisions should be employed when these materials are used.

Typically, shotcrete repair materials comprise a blend of materials, as indicated in Table 20.2.

20.3—Shotcrete placement methods for repair

Selection of the shotcrete placement method includes these important steps:

(1) Selection of the method (wet-mix or dry-mix) that best reconstructs the strength, integrity, and performance required by the structure's original design and current situation.

(2) Selection of the method of placement that will deliver the repair material onto the prepared surface, substrate, and repair configuration.

(3) Checking the feasibility of the selected shotcrete placement, taking into consideration site conditions, time available to complete the operation, and the specific means of conveying the shotcrete to the repair location.

The placement method should deliver the shotcrete to the prepared surface or substrate with specified results. The shotcrete should achieve satisfactory bond to the receiving surface or structure. The shotcrete placement should facilitate filling the prepared cavity without segregation or entrapment of rebound, and fully encapsulate any structural, reinforcing steel, or welded wire reinforcement. Without achieving the aforementioned requirements, the repair may not perform its intended structural, protective, and aesthetic duties.

The bond achieved depends to large degree on mechanical interlocking with the prepared receiving surface. For this to occur, a high velocity should be used to compact the applied shotcrete to bring it into intimate contact with the prepared surface. The shotcrete mixture should also have an adequate cement content to adhere and bond with the prepared surface.

Constructability is defined by these questions: Can the shotcrete repair be completed within the constraints specified by the engineer or owner? Can the necessary shotcrete and ancillary equipment be located in proximity to the repair area? Will the shotcrete placement system allow the repaired structure to be placed in service within the time specified? Is the approach to shotcrete application conducive to the underground working environment? Are there experienced contractors available for the underground project?

20.3.1 *Dry-mix shotcrete*—The dry-mix process varies depending on the necessary thickness and orientation. Where the repair is thick, the process may involve the placement of multiple layers. Otherwise, overly thick individual layers may result in sloughing. The use of silica fume improves adhesion and cohesion of the shotcrete and reduces sloughing. Typical problems with shotcrete repairs include the presence of voids due to encapsulated rebound and shrinkage due the high cement content, improper curing, or excessive water content used during application. Shotcrete can be placed on demand; thus, this system has operational flexibility. Because the volume of shotcrete associated with repair and rehabilitation is usually small, limited shotcrete production capacity is required because preparatory work and finishing consumes most of the production time.

20.3.2 *Wet-mix shotcrete*—In the wet-mix process, premixed repair materials are shot onto the substrate with compressed air. Additives and admixtures used to enhance the shotcrete mixture include silica fume, fibers, and air-entraining admixtures, which can enhance the durability of the repair material (specifically, improve freezing-and-thawing resistance).

Intermittent shotcrete placement required in limited repair areas using relatively small volumes can lead to production problems, waste of materials, and setup problems if system selection and production planning are not properly conceived.

20.4—Quality assurance requirements for rehabilitation of underground structures

The QA program for rehabilitation of underground facilities should conform to the recommendations found in Chapter 9.

20.5—Repair considerations

Numerous factors influence shotcrete repairs of existing underground structures, including the type of construction, facility operations, and the severity of the defects. The elements that most directly affect the selection of the shotcrete process are:

(a) Strength of repair material (largely dictated by the strength of the original construction)

(b) Durability requirements (a function of the strength and the long-term suitability of the repair configuration)

(c) Environmental setting of the repair location (of prime importance due to the varied environments that exist within the underground setting [the presence of water, atmospheric/temperature changes in ventilation shafts, shaft stations, and portal locations]; and the chemical composition of the groundwater and soil and rock that surround the tunnel have a strong influence on the selection of proper repair products)

(d) Allowable time frame for the implementation of the repair (one of the most important elements in the shotcrete selection process). The time frame is dependent on the owner's concern for public or worker safety and operations, including hours of shutdown for repair construction

Table 20.6—Example guide specification for repair and rehabilitation

Section/ Part/ Article	Recommended specification language	Notes to the Specifier
20.1	On the project drawings, the engineer shall locate and identify areas to be repaired.	Archival, as-built, and facility operations drawings are a considerable asset when repair and rehabilitation of structure is an issue.
20.2	Using acceptable methods, remove deteriorated rock or substrate that cannot be repaired in place.	
20.3	Prepare surface repair boundaries to shotcrete as outlined in ACI 506R.	Sampling and testing per ASTM C823/C823M, C42/C42M, and C1604/C1604M. Nondestructive test methods or simple sounding can determine the extent of the condition in need of remediation.
20.4	Clean surface of the exposed structural and reinforcing steel, rock, and concrete using high-pressure air and water.	
20.5	Exposed corroded reinforcing steel encountered in the repair process requires shotcrete to be removed around the circumference of the bar.	
20.6	Heavy oxides or other bond-inhibiting materials must be removed by a cleaning method acceptable to the engineer.	
20.7	Reinforcing bars damaged during removal operations or with critical section loss may require repair or replacement and should be subject to structural assessment and, if necessary, replacement or supplementation.	
20.8	In certain situations, special coatings may be applied to add additional protection to the structural steel and reinforcing bars.	
20.9	Surfaces of existing concrete exposed to receive the repair material must be sound, clean, and free from bond-inhibiting materials. An ideal sound surface is one of adequate compressive strength, free of defects, with matrix aggregate bonded to cement matrix.	For cementitious repair materials, the prepared substrate should be brought to an SSD condition before application of the repair material.
20.10	After initial removal, repair surfaces must be sounded for delaminations, laitances, and voids.	
20.11	Any rock or substrate areas found to be unsound must be rechipped or removed.	Sandblasting or high-pressure water-blasting should be used to remove the damaged surface layer caused by chipping.
20.12	Complete repair to line, grade, and tolerances indicated in project drawings and specifications.	Surface finishing should be commensurate with original architectural considerations.
20.13	Complete materials testing as specified.	Assess testing data to confirm material and structural properties specified.

and maintenance of clearance envelopes for revenue service during the rehabilitation construction period.

A successful rehabilitation project culminates in the economical implementation of repairs to the underground structure. These repairs should be durable, easy to perform, and capable of being implemented rapidly during non-operational hours. In addition, they should not constitute a safety hazard to facility operations. It should be recognized that each underground rehabilitation project is unique. Attention to specific site requirements and conditions ultimately dictate the suitability of the shotcrete process as a viable means of repair or rehabilitation.

20.6—Recommended specifications

Recommended specifications for repair and rehabilitation are provided in Table 20.6. 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 21.1—Suggested measures for basis of payment for shotcrete

Pay item	Category or application	Suggested pay unit
1	Category I	Linear meter
2	Category II	Linear meter
3	Category Portal A	Linear meter
4	Category Portal B	Linear meter
5	Cross Passage Category A	Each
6	Cavern Zone, 3 in. (75 mm) thick	Square meter

CHAPTER 21—MEASUREMENT AND PAYMENT

21.1—Basis for payment

Payment methods should be based on a predetermined quantity of readily verifiable completed work. Refer to Table 21.1.

Table 21.2—Example guide specification for basis of payment

Section/ Part/ Article	Recommended specification language	Notes to the Specifier
21.1	Measure of completed work: Shotcrete for the ______ (tunnel, drift, cavern, or the like) will be measured by the ______ (linear ft [linear meter], square yard [square meter], cubic yard [cubic meter]) of complete work certified and measured for payment by the engineer.	The preferred method for measurement of shotcrete is for some unit of in-place shotcrete because the amount of rebound and waste is usually unknown and always controversial. This is particularly true for underground projects because the amount of rebound is greater when shooting overhead and when shooting irregular overhead surfaces and irregular reinforcement. In addition, relatively long slicklines may cause significant waste material during clean-out on a regular basis or plug removal.
	1. The measurement of square yard (square meter) shall be along the centerline of the completed work. 2. The measurement of square yard (square meter) shall be of completed shotcrete surface area having the minimum specified shotcrete thickness that also meets all other requirements of these specifications. 3. The measurement of cubic yard (cubic meter) shall be of completed shotcrete using the measured area of completed shotcrete, multiplied by the minimum specified thickness for its location, which also meets all other requirements of these specifications. Thickness and area measurements shall be performed by the engineer.	The excavation surface is irregular and highly dependent on the overbreak. Overbreak is dependent on the contractor's means and methods and the geology. Typically, the contractor must assume a certain amount of overbreak and the backfill of this overbreak with shotcrete is the contractor's risk. Therefore, the payment is based on the surface area, while the thickness is assumed "as shown on drawings" and the contractor's risk. Only if the overbreak is over certain limits and not caused by the contractor's means and methods will additional backfill shotcrete beyond the contractual limits be paid per volume as measured in the field.
21.2	Basis for payment: The accepted quantities, determined as provided in Example Specification 21.1, will be paid for at the contract unit price bid per unit of measurement for the pay items listed in the accompanying table, which price and payment will be full compensation for the work prescribed in this section.	Refer to the suggested pay items in Section 21.1. In some projects, the shotcrete is not measured separately for payment. Its work is incidental to the work specified for tunnel initial supports, which is normally paid by unit prices, including all labor, material, tests, and equipment necessary to complete the work.

21.2—Recommended specifications

Recommended specifications for basis of payment are provided in Table 21.2. 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 22—REFERENCES

Committee documents are listed first by document number and year of publication followed by authored documents listed alphabetically.

American Concrete Institute (ACI)

ACI 318-19—Building Code Requirements for Structural Concrete and Commentary

ACI 506R-16—Guide to Shotcrete

ACI 506.1R-20—Guide to Fiber-Reinforced Shotcrete

ACI 506.2-13(18)—Specification for Shotcrete

ACI 506.4R-19—Guide for the Evaluation of Shotcrete

ACI 506.6T-17—Visual Shotcrete Core Quality Evaluation

ACI 544.3R-08—Guide for Specifying, Proportioning, and Production of Fiber-Reinforced Concrete

ACI CCS-4(20)—Shotcrete for the Craftsman

ACI CP-60(15)—Craftsman Workbook for ACI Certification of Shotcrete Nozzleman

ACI CPP-660.1-20—Shotcrete Nozzleman and Nozzleman-in-Training (Dry-Mix Process) and Shotcrete Nozzleman and Nozzleman-in-Training (Wet-Mix Process)

ACI CPP-661.1-19—Certification Policies for Shotcrete Inspector

American Shotcrete Association (ASA)

Underground Committee Position Statement #1—Spraying Shotcrete Overhead in Underground Applications, *Shotcrete*, Summer 2019, pp. 46-49.

Underground Committee Position Statement #2—Spray Shotcrete on Synthetic Sheet Waterproofing Membranes, *Shotcrete*, Fall 2019, pp. 35-37.

ASTM International

ASTM A185/A185M-07—Standard Specification for Steel Welded Wire Reinforcement, Plain, for Concrete

ASTM A615/A615M-20—Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement

ASTM A820/A820M-16—Standard Specification for Steel Fibers for Fiber-Reinforced Concrete

ASTM C33/C33M-18—Standard Specification for Concrete Aggregates

ASTM C42/C42M-20—Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

ASTM C78/C78M-18—Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)

ASTM C94/C94M-20—Standard Specification for Ready-Mixed Concrete

ASTM C143/C143M-20—Standard Test Method for Slump of Hydraulic-Cement Concrete

ASTM C150/C150M-20—Standard Specification for Portland Cement

ASTM C231/C231M-17a—Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

ASTM C330/C330M-17a—Standard Specification for Lightweight Aggregates for Structural Concrete

ASTM C457-09—Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete

ASTM C618-19—Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

ASTM C642-13—Standard Test Method for Density, Absorption, and Voids in Hardened Concrete

ASTM C685/C685M-17—Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing

ASTM C823/C823M-12(2017)—Standard Practice for Examination and Sampling of Hardened Concrete in Constructions

ASTM C989/C989-18a—Standard Specification for Slag Cement for Use in Concrete and Mortars

ASTM C1074-19e1—Standard Practice for Estimating Concrete Strength by the Maturity Method

ASTM C1116/C1116M-10a(2015)—Standard Specification for Fiber-Reinforced Concrete

ASTM C1140/C1140M-11(2019)—Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels

ASTM C1141/C1141M-15—Standard Specification for Admixtures for Shotcrete

ASTM C1240-20—Standard Specification for Silica Fume Used in Cementitious Mixtures

ASTM C1436-13—Standard Specification for Materials for Shotcrete

ASTM C1480/C1480M-07(2012)—Standard Specification for Packaged, Pre-Blended, Dry, Combined Materials for Use in Wet or Dry Shotcrete Application

ASTM C1550-20—Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel)

ASTM C1602/C1602M-18—Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete

ASTM C1603-16—Standard Test Method for Measurement of Solids in Water

ASTM C1604/C1604M-05(2019)—Standard Test Method for Obtaining and Testing Drilled Cores of Shotcrete

ASTM C1609/C1609M-19a—Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)

Authored documents

Banthia, N.; Trottier, J. F.; Beaupré, D.; and Wood, D., 1994, "Properties of Steel Fiber Reinforced Shotcrete," *Canadian Journal of Civil Engineering*, V. 21, No. 4, pp. 564-575. doi: 10.1139/l94-058

Beaupré, D., 1994, "Rheology of High-Performance Shotcrete," PhD thesis, University of British Columbia, Vancouver, BC, Canada, 250 pp.

Beaupré, D.; Dufour, J.-F.; Lamontagne, A.; and Pigeon, M., 1996, "Powdered Air-Entraining Admixture in Dry-Mix Shotcrete," *Sprayed Concrete Technology for the 21st Century*, Proceedings of the ACI/SCA International Conference on Sprayed Concrete/Shotcrete, Edinburgh, UK, Sept., pp. 1-7.

Bernard, E. S., 2004, "Design Performance Requirements for Fibre-Reinforced Shotcrete Using ASTM C1550," *Proceedings*, 2nd International Conference on Engineering Developments in Shotcrete, Cairns, Australia, Oct. 4, pp. 67-80.

Bernard, E. S., 2013, "Influence of Test Machine Control Method on Apparent Performance of ASTM C1550 Fiber Reinforced Concrete Panels," *Advances in Civil Engineering Materials*, V. 2, No. 1, pp. 163-177.

Bernard, E. S., 2019, "Predicting Crack Widths in FRC/Reinforced Concrete Members Using Small Deformation Post-Crack Parameters," *Structural Concrete*, V. 20, No. 6, pp. 1464-1477. doi: 10.1002/suco.201900083

Bernard, S., 2005, "Early-Age Test Methods for Fiber-Reinforced Shotcrete," *Shotcrete*, V. 7, No. 2, Spring, pp. 16-20.

Campbell, K., 1999, "Shrinkage Cracking of Fiber Reinforced Dry-Mix Shotcrete," master's thesis, University of British Columbia, Vancouver, BC, Canada, 120 pp.

Clements, M., 2003, "Shotcreting in Australian Underground Mines: A Decade of Rapid Improvement," *Shotcrete*, V. 5, No. 2, Spring, pp. 6-9.

Dufour, J. F.; O'Donnell, J. D. P.; and Ballou, M., 2002, "Determination of Early Age Ductility of Steel Fiber-Reinforced Shotcrete Lining System in INCO's Stobe Mine," NARMS-TAC 2002, University of Toronto, Toronto, ON, Canada, pp. 865-879.

Ginouse, N., and Jolin, M., 2013, "Material Velocity at the Nozzle," *Shotcrete*, V. 15, No. 4, pp. 22-24.

Grimstad, E.; Kankes, K.; Bhasin, R.; Magnussen, A. W.; and Kavnia, A., 2002, "Rock Mass Quality Q Used in Designing Reinforced Ribs of Sprayed Concrete and Energy Absorption," *Fourth International Conference on Sprayed Concrete*, Davos, Switzerland, Sept. 22-26, pp. 134-151.

Jolin, M.; Beaupré, D.; Pigeon, M.; and Lamontagne, A., 1997, "Use of Set Accelerating Admixtures in Dry-Mix Shotcrete," *Journal of Materials in Civil Engineering*, ASCE, V. 9, No. 4, pp. 180-184. doi: 10.1061/(ASCE)0899-1561(1997)9:4(180)

Kaiser, P. K.; Diederichs, M. S.; Martin, C. D.; Sharp, J.; and Steiner, W., 2000, "Underground Works in Hard Rock Tunneling and Mining," Keynote Lecture at GeoEng2000, Melbourne, Australia, Technomic Publishing Co., V. 1, pp. 841-926.

Kaiser, P. K.; McCreath, D. R.; and Tannant, D. D., 1996, *Canadian Rockburst Support Handbook*, Geomechanics Research Center, Laurentian University, Sudbury, ON, Canada, Jan.

Kirstin, H. A. D., 1983, "The Combined Q/NATM System—The Design and Specification of Primary Tunnel Support," *South African Tunnelling*, V. 6, No. 1, pp. 18-24.

Mahar, J. W.; Parker, H. W.; and Wullner, W. W., 1975, "Shotcrete Practice in Underground Construction," *Report for Federal Railroad Administration*, University of Illinois Civil Engineering Department, U.S. Department of Transportation, 475 pp.

Morgan, D. R.; Chen, L.; and Beaupré, D., 1995, "Toughness of Fibre-Reinforced Shotcrete," *Shotcrete for Underground Support VII*, pp. 66-87.

Morgan, D. R.; Heere, R.; McAskill, N.; and Chan, C., 1999a, "Comparative Evaluation of System Ductility of Mesh and Fibre-Reinforced Shotcretes," *Shotcrete for Underground Support VIII*, ASCE, pp. 216-239.

Morgan, D. R.; McAskill, N.; and Heere, R., 1999b, "Determination of Early-Age Compressive Strength of Shotcrete," *Third International Symposium on Sprayed Concrete*, Gol, Norway, Sept., pp. 347-357.

Morgan, D. R., and Pigeon, M., 1992, "High Performance Shotcrete," *Proceedings from the Half-Day Presentations of the 4th Semiannual Meeting of the Network of Centers of Excellence on High-Performance Concrete*, Toronto, ON, Canada, Oct. 6, pp. 31-56.

Norwegian Concrete Association, 2003, "Sprayed Concrete for Rock Support—Technical Specifications, Guidelines and Test Methods," *NCA Publication* No. 7, 108 pp.

Papworth, F., 2002, "Design Guidelines for the Use of Fiber-Reinforced Shotcrete in Ground Support," *Shotcrete*, V. 4, Spring, pp. 16-21.

Parker, H. W., 1976, "Field-Oriented Investigation of Conventional and Experimental Shotcrete for Tunnels," PhD thesis, University of Illinois at Urbana-Champaign, Champaign, IL, 628 pp.

Pigeon, M.; Lacombe, P.; Beaupré, D.; and Cloutier, E., 2000, "Properties of Dry-Mix Shotcrete Containing Supplementary Cementitious Materials," *Concrete International*, V. 22, No. 10, Oct., pp. 51-57.

Prudencio, L. R. Jr.; Armelin, H. S.; and Helene, P., 1996, "Interaction between Accelerating Admixtures and Portland Cement for Shotcrete: The Influence of the Admixture's Chemical Base and the Correlation between Paste Tests and Shotcrete Performance," *ACI Materials Journal*, V. 93, No. 6, Nov.-Dec., pp. 619-628.

Radomski, S.; Morgan, R.; Zhang, L.; and Graham, D., 2019, "Structural Modifications to Hydroelectric Turbine Draft Tube Ceiling," *Shotcrete*, V. 21, Summer, pp. 22-34

Tatnall, P. C., 2002, "Shotcrete in Fires: Effects of Fibers on Explosive Spalling," *Shotcrete*, V. 4, Fall, pp. 10-12.

Vandewalle, M., and Bekaert, N. V., 2005, *Tunnelling is an Art*, Belgium, 400 pp.

Zhang, L., 2012, "Accelerator Dosing Pump Calibration and Verification," *Shotcrete*, V. 14, Summer, pp. 42-44

Zhang, L.; Morgan, D.; and Mindess, S., 2016, "Comparative Evaluation of Transport Properties of Shotcrete Compared to Cast-in-Place Concrete," *ACI Materials Journal*, V. 113, No. 3, May-June, pp. 373-384.

American Concrete Institute
Always advancing

As ACI begins its second century of advancing concrete knowledge, its original chartered purpose remains "to provide a comradeship in finding the best ways to do concrete work of all kinds and in spreading knowledge." In keeping with this purpose, ACI supports the following activities:

- Technical committees that produce consensus reports, guides, specifications, and codes.
- Spring and fall conventions to facilitate the work of its committees.
- Educational seminars that disseminate reliable information on concrete.
- Certification programs for personnel employed within the concrete industry.
- Student programs such as scholarships, internships, and competitions.
- Sponsoring and co-sponsoring international conferences and symposia.
- Formal coordination with several international concrete related societies.
- Periodicals: the ACI Structural Journal, Materials Journal, and Concrete International.

Benefits of membership include a subscription to Concrete International and to an ACI Journal. ACI members receive discounts of up to 40% on all ACI products and services, including documents, seminars and convention registration fees.

As a member of ACI, you join thousands of practitioners and professionals worldwide who share a commitment to maintain the highest industry standards for concrete technology, construction, and practices. In addition, ACI chapters provide opportunities for interaction of professionals and practitioners at a local level to discuss and share concrete knowledge and fellowship.

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

American Concrete Institute
Always advancing

38800 Country Club Drive
Farmington Hills, MI 48331 USA
+1.248.848.3700
www.concrete.org

The American Concrete Institute (ACI) is a leading authority and resource worldwide for the development and distribution of consensus-based standards and technical resources, educational programs, and certifications for individuals and organizations involved in concrete design, construction, and materials, who share a commitment to pursuing the best use of concrete.

Individuals interested in the activities of ACI are encouraged to explore the ACI website for membership opportunities, committee activities, and a wide variety of concrete resources. As a volunteer member-driven organization, ACI invites partnerships and welcomes all concrete professionals who wish to be part of a respected, connected, social group that provides an opportunity for professional growth, networking and enjoyment.

9 781641 951982