Advances in Shotcrete Technology for Ground Support in Tunnels and Mines in North America

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Paper presented in October 2021 during the Tunneling Association - Canada conference in Toronto.

ABSTRACT

In recent years, shotcrete has been widely used for ground support in civil tunnels and mines in North America. Shotcrete technologies have advanced with robust robotic sprayers, high-performance shotcrete mixture designs, and high-performance fiber reinforcement in conjunction with rigorous qualification of shotcrete nozzlemen and QC inspection and testing programs. Design engineers and contractors are using shotcrete more and more often for various underground applications including ground support and final linings in tunnels in soft ground and hard rock mines, as well as in repair and rehabilitation projects in railway tunnels and other underground openings. Large underground caverns have been constructed using shotcrete as the initial liner in San Francisco and Los Angeles, and for both the initial liner and final liner in New York and Washington D.C. This article focuses on recent underground shotcrete technology developments from project experience and provides lessons learned. It also demonstrates that proper quality control and shotcrete qualification programs are critical for successful shotcrete projects.

Introduction

Shotcrete is a process for pneumatically conveying concrete materials at high velocity to a receiving surface to achieve in-place compaction. While shotcrete has been used for over a century, the use of shotcrete for ground support in tunnels, mines, shafts, and other underground structures has become increasingly popular during the past decade (Ref. 1-9). Advances in shotcrete technology include using high-performance shotcrete mixtures, advanced robotic sprayers operated by a remote controller, alkali-free accelerator, and high-performance fibers, including both macro-synthetic fibers and steel fibers.

During the past decade, the authors have worked on a number of major civil tunnel and mining projects across the US and Canada. The authors have provided shotcrete mixture designs, monitored trial shoots, and tested shotcrete both in the field and in the laboratory. Through these projects, the authors have accumulated over a decade of data on shotcrete performance and project experience as discussed in this paper.

CHARACTERISTICS REQUIRED OF SHOTCRETE MATERIALS FOR SUCCESSFUL UNDERGROUND SHOTCRETE APPLICATION:

- Workable, i.e., cohesive
- Have proper slump and consistency, not segregating during transport or pumping
- Pumpable, i.e., have good workability for pumping
- Shootable, i.e., work compatibly with the shotcrete pump, hose, and nozzle, and be efficiently managed/controlled by the nozzleman
- Constructable, i.e., the shotcrete mixture as batched, supplied, and transported must be able to be applied as designed/planned, and not cause any delay to the construction schedule
- Incidents, such as excessive loss of slump or temperature rise, flash set, hose plugs, and shotcrete fallout occurrences should be minimized during construction.

Shotcrete mixture design for underground support

Shotcrete can be used as an initial liner for ground support during the tunneling process. In soft ground tunneling methods, such as The New Austrian Tunneling Method (NATM), also known as the Sequential Excavation Method (SEM) or Sprayed Concrete Lining method (SCL), shotcrete is a critical component for tunnel construction. Large SEM caverns include Beacon Hill station, Seattle, 2006; Chinatown Central Subway station, San Francisco, 2016; Regional

Connector, Los Angeles; and Purple Line transit, Washington D.C. Shotcrete can also be used for hard rock mining with tunnel boring machines (TBM) or with drill and blast methods to provide final liner support. These projects include hydro-electrical tunnel projects such as John Hart Dam underground tunnel, Campbell River, BC; Upper Lillooet Hydroelectrical Project, Pemberton, BC; Kemano T2 completion project, Kemano, BC; and water supply tunnel projects, such as the Seymour-Capilano Completion project, North Vancouver, BC. All of these projects required shotcrete to be applied in both overhead and vertical orientations; to develop sufficient early age compressive strength (up to 24 hrs) for ground support; to meet specified compressive strength at 7 & 28 days; to achieve specified bond strength to the rock; and to meet durability requirements. Typical specified performance requirements are listed in Table 1.

Mixture Design

Shotcrete mixtures are designed to meet the specified performance requirements and to provide suitable constructability. Compared to cast-in-place concrete, shotcrete mixtures typically have:

- A higher cementitious materials content to minimize rebound and provide suitable shootability.
- Enhanced workability for pumping, and dispersion of liquid accelerator addition at the nozzle (when used).
- Lower coarse aggregate content, i.e., higher sand content to minimize rebound and facilitate pumping and shooting.
- An extended slump retention time to meet the construction schedule requirements.

Supplementary cementitious materials (SCMs) are widely used in shotcrete. These include, but are not limited to, fly ash, silica fume, and slag. SCMs react with calcium hydroxide, a by-product of the cement hydration process, to form Calcium-Silica-Hydrate (CSH) through the pozzolanic reaction process. This results in reduced porosity and enhanced compressive strength and durability in the applied shotcrete. SCMs have similar or smaller particle sizes than cement, and based on that, they can help compact or densify the mixture through grain-size distribution. In addition, fly ash and silica fume particles are mainly spherical in shape, which enhances the pumping and shooting characteristics of the mix. Each type of SCM is added at a certain percentage by mass of total cementitious materials for the shotcrete to meet performance and constructability requirements. Table 2 shows a typical wet-mix shotcrete mixture design for ground support.

Water : cementitious ratio (w/cm)	Max. 0.45
Early age compressive strength:	1.5 hrs > 1 MPa, 6 hrs > 4 MPa, 24 hrs > 10 MPa
Compressive Strength:	10 MPa at 3 days, 20 MPa at 7 days, 35 MPa at 28 days,
Permeability:	Boiled Absorption: <8%; Volume of Permeable Voids: <17%
Set time:	Initial set <15 minutes; Final set <50 minutes
Slump (wet-mix):	150-200 mm
Shotcrete Temperature:	10-25 °C
Flexural strength:	Minimum of 4 MPa at 28 days
Flexural toughness performance (TPL) to ASTM C1609:	Level III at 7 days
Flexural toughness to ASTM C1550:	250 Joules (3 days); 350 Joules (7 days); 450 Joules (28 days)
Air content:	3-6% as-shot
Air void spacing factor:	Maximum of 300 um
Chloride ion permeability:	Maximum 1000 Coulombs at 56 days
Bond strength:	Minimum of 1 MPa at 28 days

Table 1: Typical Performance Requirement for Shotcrete in Underground Applications

Material	**Mass per m^3 SSD Agg, [kg]**
Cement Type GU	410
Silica Fume	40
Coarse Aggregate (10-5 mm, SSD)	430
Fine Aggregate (SSD)	1320
Estimated Water, L	185
Superplasticizer, L	1
Macro synthetic Fiber	7
Hydration Control Admixture, L	1
Air Content (4.5-6.5%)	3.5
Total	2394

Table 2: Wet-mix design from the Upper Lillooet Hydroelectric Project (Ref. 9)

Alkali-free accelerator

Alkali-free accelerator (AFA) is added into wet-mix shotcrete at the nozzle to accelerate the setting time and early age compressive strength development from 1-24 hours. The rate of early-age compressive strength development is critical for ground support as it will reduce the construction cycling time for excavation and ground support. Since early 2000, AFA has been used in the shotcrete industry to replace alkali-based accelerators.

AFA has a pH value of 2-4, which is similar to carbonated cola drinks. AFA can be added as a liquid chemical admixture at the nozzle for wet-mix shotcrete applications or as a powder chemical admixture that is preblended into the shotcrete mixture for dry-mix shotcrete applications.

For most ground support requirements, an early-age compressive strength of 1.0-2.0 MPa (145-290 psi) is required for the applied shotcrete to facilitate construction activities. AFA must be added at the proper dosage to achieve suitable early-age compressive strength development. Based on the authors' experience with many tunneling projects, it generally takes an AFA dosage of about 4-6% by mass of cement to reach the required strength in about 1-3 hours. Variations in the early-age compressive strength development are dependent on the shotcrete mixture design, including the type of cement and chemical admixtures used, the accelerator brand and performance, the shotcrete temperature, the ambient temperatures, and the proper handling and dispensing of accelerator and shooting skills of the shotcrete nozzlemen. Fig. 1 shows typical early-age compressive strength development with AFA dosage when plotted to the J1-J2-J3 curve template developed by the Austrian Concrete Society (Ref. 10, 11). J2 is generally considered the minimum performance requirement for shotcrete early-age compressive strength development for most ground support projects.

When different types of cement are used, such as Type V or Type GUL (Type GU with 15% limestone), the set time may be delayed. Therefore, a higher dosage of AFA is required to develop the early-age compressive strength properly. AFA will, however, reduce the later-age compressive strength, including the 7 and 28-day compressive strengths. Fig. 2 shows the compressive strength development for a wet-mix shotcrete with 0, 4%, 6% and 8% AFA. It shows that with 8% AFA added into the shotcrete, the compressive strength at 28 days could reduce from 62 MPa (9000 psi) to about 36 MPa (5200 psi). Therefore, it is important to add the accelerator at the design/specified dosage to minimize adverse effects on later-age compressive strength development.

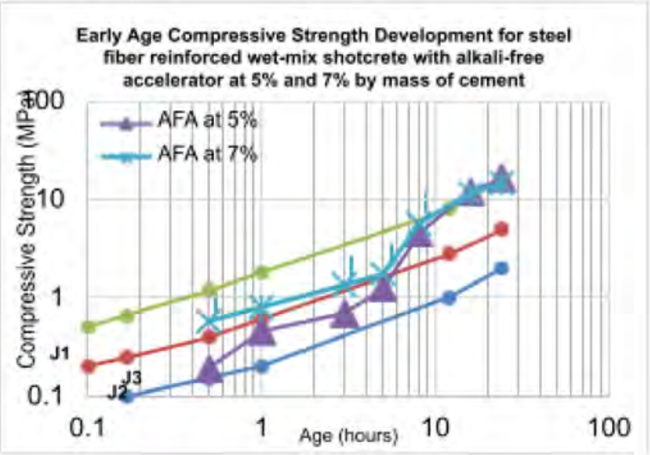

Fig. 1 Early age compressive strength development for steel fiber reinforced shotcrete mixture with 15% fly ash at 5% and 7% AFA

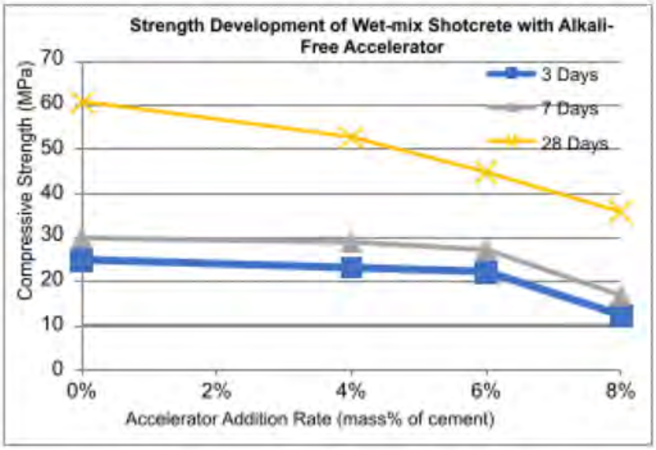

Fig. 2: Effect of Accelerator Dosages on Compressive Strength from 3 to 28 days

Fiber-reinforced shotcrete advancement

The most significant property of fiber-reinforced shotcrete (FRS) is the energy absorbed after the shotcrete cracks, i.e., the flexural toughness. After shotcrete cracks, fibers are pulled out or fractured during the cracking process, thereby redistributing loads and controlling crack propagation as the FRS lining system experiences deformation. Both macrosynthetic and steel fiber are used in wet-mix shotcrete in underground applications throughout North America. The fibers are used to replace, either partially or completely, the steel mesh in the ground support system, reduce the construction cycle time, and generally provide overall better performance in ground support. Combining fiber-reinforced shotcrete with a suitably designed rock anchor system is one of the most efficient ground support systems used in many mines and civil tunnels.

Design of the FRS is commonly based on performance-based design methods which utilize flexural toughness testing results. Typical flexural toughness test methods include the following:

- ASTM C1550 Determination of Flexural Toughness with Central Loaded Round Panel Test
- ASTM C1609 Determination of Flexural Toughness with Third Point Loaded Beam Test
- RILEM TC 162-TDF: Test and design methods for-steel fiber-reinforced concrete (notched beam test)
- British Standard (BS) EN 14651 Test for metallic fiber concrete – measuring flexural tensile strength (notched beam test)

The flexural toughness, the residual strength, and the peak load (peak strength) are the most important factors when evaluating the performance of fiber-reinforced shotcrete.

During the past decade, the authors have conducted over 5000 flexural toughness and residual tensile strength tests for FRS used in underground projects across the US and Canada. Examples of these test results will be analyzed and published in a future paper. Based on project experience, there are three typical project specifications for flexural toughness performance requirements for FRS utilized in North America.

Toughness performance level (TPL) based on the ASTM C1609 test

When the TPL is specified, it requires the shotcrete test panel to be cut into beams with dimensions of 100x100x350 mm (4x4x14 in.) and tested to ASTM C1609. Sometimes, shotcrete samples can be shot directly into 150x150x550 mm (6x6x22 in.) beam molds, with both ends slanted to prevent accumulation of rebound. Over 3000 FRS beams have been tested by the authors to ASTM C1609 since 2011. It has been found that if the TPL meets the Toughness Performance Level III, it generally meets the support requirements for most ground conditions.

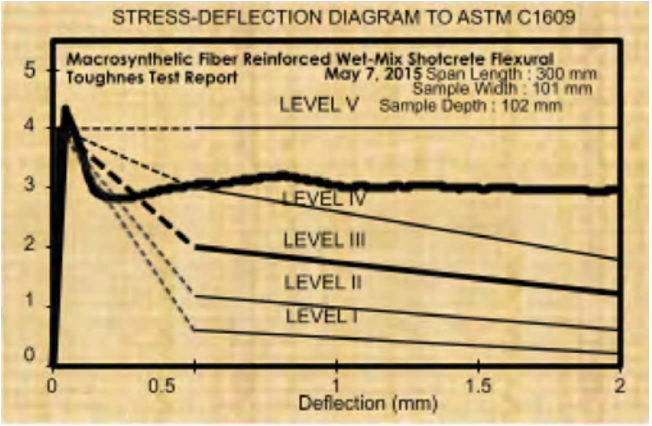

Fig. 3: Stress-Deflection Curve for Flexural Toughness Test to ASTM C1609

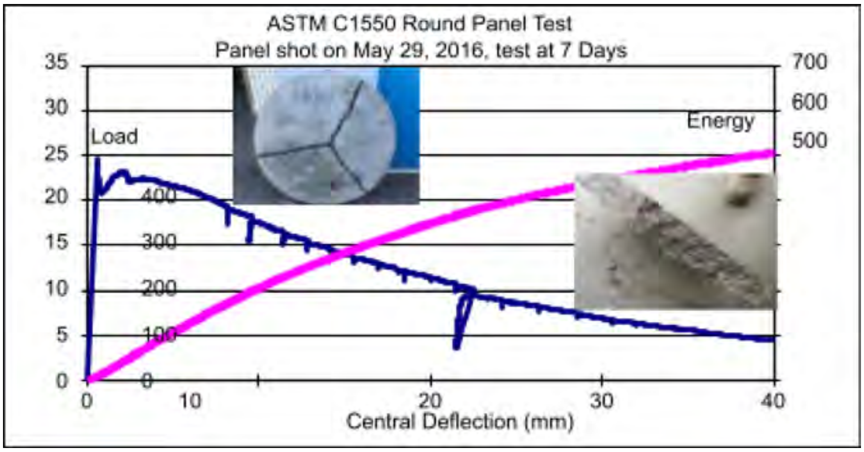

Fig. 4: Stress-Deflection Curve for Flexural Toughness Test to ASTM C1550

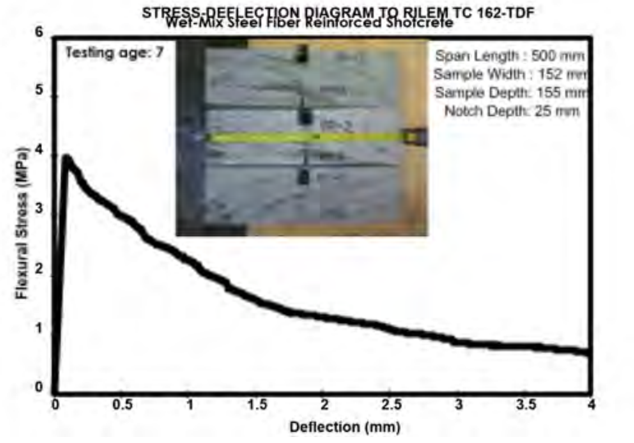

Fig. 5: Residual Tensile Stress vs Deflection for FRS Beam to BS EN 14651 / RILEM-TC-162-TDF

Round determinate panel (RDP) method based on ASTM C1550 test method

When the RDP method is specified, it requires samples of round determinate panels (RDP) to be shot with dimensions of 800 mm (31.5 in.) in diameter and 75 mm (3 in.) in thickness. The RDPs are tested to ASTM C1550 and the total energy absorbed up to 40 mm (1.6 in.) deflection is reported. Fig. 4 shows a typical flexural toughness load vs. deflection test result. Over 2000 FRS round panels have been tested to ASTM C1550 by the authors since 2011. If the flexural toughness exceeds 320-450 Joules, it generally meets the support requirements for most ground conditions. For hard rock tunnels, a flexural toughness of over 320-350 Joules has been commonly specified to meet the general ground support requirements. For soft ground, such as SEM, flexural toughness of 450 Joules has been specified to meet the ground support requirements.

Notched beam method based on BS EN 14651 / RILEM-TC-162-TDF residual tensile strength

The residual tensile strength of FRS can also be tested by the BS EN 14651 notched beam test method. The shotcrete beam is pre-cracked by saw cutting a notch 25 mm (.98 in.) deep into the bottom of the 150 mm x 150 mm (6x6 in.) cross-section beam at its center. A three-point bending load is applied to the beam. Fig. 5 shows a typical residual tensile stress vs. deflection curve for the notched beam test.

Both ASTM C1609 and ASTM C1550 can provide sufficient information on flexural toughness for FRS. They are applicable for either steel fiber or macrosynthetic-fiber-reinforced shotcrete. BS EN 14651 /

RILEM-TC-162-TDF employs a notch in the beam, introducing stress intensity. This test method was originally developed by RILEM to study the residual tensile strength based on fracture mechanics, though it is generally agreed that a crack will propagate through the notch. The authors have tested approximately 50 beams with this test method in the past decade. Most specifications for civil tunnel shotcrete require either ASTM C1609 or ASTM C1550 tests or both. Few specifications in North America require the BS EN 14651 or RILEM-TC-162-TDF tests.

Qualification of shotcrete mixtures and nozzlemen

Before construction, the project specification requires the shotcrete mixture to be prequalified. This is typically conducted at least 60 days prior to shotcrete placement. For very large projects where shotcrete is part of the tunneling or mining ground support process, such as SEM, qualification of the shotcrete mixture could start as early as 6 months before construction start. Mixture qualification normally requires the shotcrete mixture to be applied with the same equipment and crew that will be used for the construction to ensure that shotcrete can be placed properly throughout the project. During the mixture qualification, test panels are shot. Plastic properties of temperature, air content, and slump (as batched), as well as air content and slump (as shot) are tested. When accelerator is used, the initial set and final set time are tested to ASTM C1117 and the early-age compressive strength is tested for up to 24 hours using the end beam test method. Cores are extracted from the test panels and tested for compressive strength, boiled absorption and volume of permeable voids, rapid chloride ion penetration, etc. Beams are cut from the test panels for flexural toughness testing to ASTM C1609. Round determinate panels (RDP) are shot and tested for flexural toughness to ASTM C1550. All of the test results should meet the project specification requirements.

An accelerator is commonly used in underground shotcrete applications. The accelerator dosage determines the set time and rate of early-age compressive strength development for shotcrete. The dosage of the accelerator should be calibrated with the accelerator dosing pump and the shotcrete pump to be used. Proper calibration of the accelerator dosage is one of the most important parts of the mixture qualification. Detailed information on accelerator dosing pump calibration can be found in (Ref. 12, 13). After the shotcrete mixture is prequalified, the shotcrete nozzlemen also need to be qualified for the project. Nozzlemen qualification requires the nozzlemen properly apply shotcrete to achieve the specified performance and ground support requirements. More specifically, qualification of the shotcrete nozzlemen requires the following:

- Nozzlemen need to understand the basics of concrete and shotcrete technology. This includes how the cement hydrates, temperature effects on shotcrete, and the effects of accelerator and other chemical admixtures on shotcrete performance.
- Workability, pumpability, and shootability: the nozzlemen should understand that the slump, or consistency of the shotcrete mixture, is critical for transport, pumping, and shooting. Overhead and vertical applications pose different challenges for shotcrete application.
- Preparation of the substrate, including cleanliness, roughness, and the receiving surface moisture condition should be saturated surface dry (SSD) to achieve optimized bond.
- Proper calibration of the accelerator dosing pump.
- Proper application of shotcrete at the specified orientation, including overhead, vertical, at 45 degrees, etc.
- Proper control of nozzle angle, distance, and shooting pattern to minimize rebound and overspray.
- Proper procedure to apply thick layers of shotcrete, including multi-layer shotcreting.
- If shotcrete falls off, either from overhead or vertical surfaces, the nozzlemen should be able to determine immediately what went wrong and how to make the necessary corrections.

The nozzlemen qualification process is essential to a successful project as it accomplishes the following:

- Educates the nozzlemen on shotcrete materials, equipment, concrete technology, and the effects of chemical admixtures including accelerator
- Prepares them for the project. Typically, the most difficult component to be shot in the shotcrete support system is selected for nozzlemen qualification shooting.

Usually, the nozzlemen qualification mockup is specifically designed for each project. Sections with the most congested reinforcement, including spliced reinforcement, lattice girders, steel sets, and other types of reinforcements and embedments are required to be shot (Fig. 6). Every nozzlemen that works on the shotcrete application for the project needs to be qualified.

Fig. 6: Reinforcement for nozzlemen qualification panels: left) spliced 25M rebar; center) lattice girder; right) Robotic sprayer nozzleman qualification for overhead and 45-degree orientation

Fig. 7: In-place set time test

Fig. 8: Early-age compressive strength test

Construction quality control inspection and testing

During shotcrete construction, a quality control inspection and testing plan is required and needs to be executed to ensure that the in-place shotcrete meets the project specification requirements, and if not, appropriate remediation actions are conducted immediately.

Field inspection for shotcrete is normally conducted with other tunnel inspection activities, such as ground monitoring, excavation progress, etc. and it normally conducted full-time by an engineer or technologist appointed by the project owner or by a shotcrete consultant appointed by the contractor.

Inspection activities typically include the following:

- Evaluation of surface roughness, free of loose particles and moisture condition prior to shotcrete application
- Shotcrete application: nozzlemen shooting skills, including control of rebound and overspray, thickness of shotcrete, and accelerator dosages if used
- Checking for any defective shotcrete, including voids, cracks, signs of accelerator overdosing, potential shotcrete failures, etc.

Field testing for shotcrete is conducted by qualified testing technicians or engineers to ensure that the plastic shotcrete meets the specified performance requirements for shotcrete pumping and application. Typically, slump, air content, and temperature for as-batched and as-shot shotcrete are tested when shotcrete is delivered to the site. Slump should be tested at the batch plant, as well as at the location where shotcrete is discharged from the transmixer into the shotcrete pump inside the tunnel. If shotcrete is required to be kept for long hauls or longer retention times, such as more than 1 shift of 12 hours, a hydration control

Fig. 9: In-place overhead shotcrete core extraction; visual inspection of core hole to evaluate shotcrete consolidation, shotcrete thickness, and bond.

Fig. 10: In-place shotcrete bond strength test and laboratory shotcrete bond strength test

admixture is normally used to keep the shotcrete workable. Whenever there is a significant loss of slump, such as a slump loss of more than 50 mm (2 in.), immediate action of retempering the shotcrete with admixture or disposal of shotcrete needs to be executed to avoid shotcrete setting inside the transmixer.

Set time testing is conducted to ASTM C1117. With accelerator added at a proper dosage, the initial set, i.e., the time when shotcrete completely loses its slump or pumpability, is less than about 15 minutes, and final set, i.e., the time when shotcrete starts to develop compressive strength, is less than about 50 minutes.

Fig. 7 shows an in-place set time test with a penetrometer needle to ASTM C1117.

Fig. 8 shows early-age compressive strength testing for shotcrete samples with the end beam testing method. If early-age compressive strength is required for ground support, such as 1.0 to 2.0 MPa (150 to 300 psi) for re-entry or to resume construction activities underneath the freshly applied shotcrete, testing needs to be conducted at multiple ages such as 2 hours, 4 hours, 6 hours, and up to 24 hours. Testing set time and early age compressive strength is common for tunneling where immediate compressive strength development is required, such as SEM tunneling.

When shotcrete hardens, in-place shotcrete consolidation, shotcrete thickness, and bond to the substrate can be evaluated by visual inspection of the core hole. Bond strength can be tested to evaluate the tensile bond strength between the shotcrete liner and the substrate rock. Bond strength can be conducted by coring and in-place testing or by extracting cores and testing bond strength in the laboratory. Tensile bond strength is sometimes specified to be a minimum 1.0 MPa. Fig. 9 shows an in-place shotcrete core hole. Fig. 10 shows in-place bond strength testing and laboratory bond strength testing. It should, however, be cautioned that some weaker rock types may fail at values below 1.0MPa in bond testing resulting in a failure of the substrate not the shotcrete bond.

New developments: mass shotcrete for underground structures

During the last few decades, more and more underground permanent structures have been built with shotcrete. Among them, mass structural shotcrete walls constructed using the "hybrid" (shoot and vibrate) method are recent developments. Heavily reinforced underground station structures with dimensions from 200 to 1500 mm (8 to 60 in.) thick are now being constructed with shotcrete. This involves a combination of structural shotcrete and underground shotcrete application technologies. The larger shotcrete structures develop higher internal temperatures due to cement's heat of hydration. When the shotcrete structures are thick enough, the heat dissipation will be of concern and will require a thermal control and protection plan.

To prevent mass concrete structures from thermal cracking, a thermal control plan (TCP) is developed as a design document. The TCP specifies the necessary measures to meet the thermal control requirements including the use of low-heat concrete mixtures, reducing shotcrete placement temperature, providing thermal blanket protection, and using internal cooling pipes. A recent mass shotcrete structural wall project in Vancouver, BC implemented a TCP using cooling pipes and thermal blankets (Ref. 14). Fig. 11 shows a shotcrete wall with heavy reinforcement and a wall with cooling pipes.

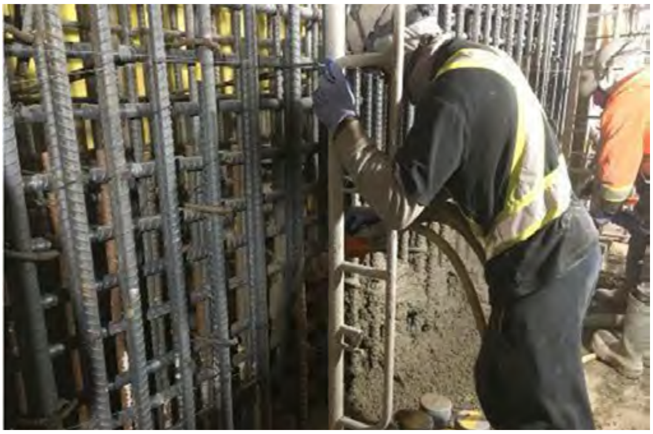

Fig. 11: Top - A mass structural wall for a sewer treatment facility constructed with mass shotcrete. Bottom: Two layers of 25M rebar with cooling pipes at 1.0 m spacing were constructed with mass shotcrete

Durability of shotcrete

More and more civil tunnels are being designed to have a service life of 70 years or more, some even with 100 years of service life. Service life for a civil tunnel primarily relies on the service life of the structure that supports the tunnel, including the final liner and other structures. When a concrete structure is designed, service life and durability requirements will override minimum structural requirements of mechanical performance including compressive strength, elastic modulus, bending moment, and tensile strength, etc.

It is critical to consider durability factors when designing for a long service life. Durability factors such as resistance to weathering, corrosion, chemical attack, alkali-aggregate reaction, carbonation, and freeze-thaw deterioration are all influenced by the concrete mixture design and transport properties of the concrete during the service life of the structure. Civil underground structures including tunnels, shafts, caverns, and others are often exposed to one or more of the above factors. Therefore, the service life of the structure is primarily dependent on the service life of shotcrete structures. The durability of the shotcrete structures is dependent on the concrete mixture design and the application process.

A question is sometimes raised about shotcrete: will it be as durable as cast-in-place concrete? A recently completed research project (Ref. 15) compared the transport properties for shotcrete to the cast-in-place concrete. Results show that properly applied shotcrete will achieve equal or better transport properties to cast-in-place concrete. Based on the research, service life was modeled using an advanced service life prediction modeling program (STADIUM), with different exposure conditions and structures. Shotcrete generally exhibits an equal or a longer time for initiation of reinforcing steel corrosion providing an extended service life (Ref. 15).

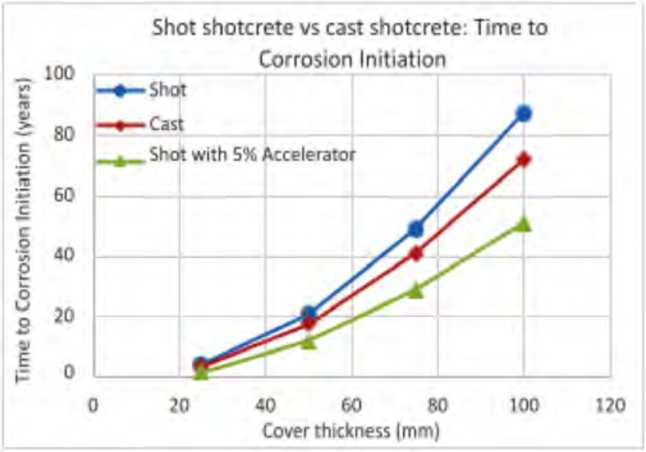

Fig. 12: Effect of accelerator for wet-mix shotcrete vs. cast-in-place concrete on time to corrosion initiation

This research also indicated equal or better durability for shotcrete provided that a moderate dosage of set accelerator is used. When accelerator is used, the quality of the shotcrete matrix tends to be degraded. While accelerator increases the rate of cement hydration and heat evolution and provides earlier strength development, it also results in a more pervious hardened concrete matrix. The chemical ions tend to migrate faster and with less resistance when accelerator is used. For example, when accelerator is added at 5% by mass of cement in shotcrete, the transport properties tend to be reduced and therefore result in reduced service life (Fig. 12, Ref. 15). While accelerator is critical for underground support to achieve rapid setting and hardening, and reliable early-age compressive strength development, the dosage of accelerator used should be closely controlled so that the shotcrete structure can achieve both the required ground support and the required durability.

Codes and standards development

Shotcrete codes, standards, and guide documents are developed and regularly updated by the American Concrete Institute (ACI) Committee 506. Project specifications are typically prepared by the design engineer with consultation and/or review from the shotcrete specialist. Here are some of the most commonly used shotcrete guides and specifications in North America:

- ACI 506.5-2018, "Guide for Specifying Underground Shotcrete." This document was updated in 2021
- ACI 506R-2015, "Guide to Shotcrete"
- ACI 506.2-2018, "Specification for Materials, Proportioning and Application of Shotcrete"
  ACI ACI - CP-60 Craftsman Workbook for ACI Certification of Shotcrete Nozzleman

These guides and specifications, together with other related documents from ACI, ASTM, CSA, AASHTO, and the US Army Corps of Engineers, provide the basis for development of a suitable QA/QC program.

Most recently, ACI 318-19 Building Code Requirements for Structural Concrete has included requirements for structural shotcrete placement (Ref. 16).

Conclusions

Shotcrete is used more and more for ground support in underground construction. The use of alkali-free accelerators (AFA) and fiber-reinforcement are two major advancements in shotcrete use in the underground environment during the past two decades. AFA is efficient in reducing shotcrete set time and development of early age compressive strength. Fibers have greatly changed ground support design and construction methods. Quality shotcrete for ground support requires the following:

- High performance shotcrete mixture
- Proper mixture qualification and nozzleman qualification program
- Rigorous construction monitoring and testing program

Shotcrete is being used much more for the final liner in tunnel construction. Examples include water conveyance tunnels for hydroelectric and water treatment projects, and road and rail tunnels. Structural shotcrete is also used increasingly in underground construction for subway stations in major metropolitan areas in North America. Mass shotcrete structures, including heavily reinforced walls, can be properly constructed with the hybrid (shoot and vibrate) structural shotcrete process together with the provision of a proper thermal control plan.

Durable shotcrete placement for ground support is critical for building durable underground structures. In particular, with many more underground structures required to have a service life of over 100 years, durability for shotcreted materials and the resulting structures, including resistance to chemical attack, is an important consideration. Research conducted by the authors has demonstrated that properly designed and applied shotcrete can provide equal or better durability compared to cast-in-place concrete.

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