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Lihe (John) Zhang
*LZhang Consulting & Testing Ltd,*

Dudley R. Morgan
*LZhang Consulting & Testing Ltd,*

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# Quality Control for Wet-Mix Fiber Reinforced Shotcrete in Ground Support

By Lihe (John) Zhang, Ph.D., P.Eng., LZhang Consulting & Testing Ltd, Vancouver, BC, Canada V4M 1S3. PH: 1-7787067198. Email: zhanglihe@gmail.com
Dr. Zhang is an Engineer at LZhang Consulting and Testing Ltd. He received his PhD in civil engineering in 2006 from the University of British Columbia, Vancouver, BC, Canada, where he conducted research on fiber-reinforced concrete. He is a member of ACI and Chair of ACI Subcommittee 506-F, Shotcrete-Underground; a member of ACI committee 506, Shotcreting; and ACI committee 544, Fiber-Reinforced Concrete.
D.R. (Rusty) Morgan, Ph.D., P.Eng. FACI. Vancouver, BC, Canada. Email: rustymorgan44@hotmail.com
Dr. Morgan was a member of ACI 506 and ACI 544 for over 30 years. He is a past President of the American Shotcrete Association. Dr. Morgan has published over 150 papers on concrete and shotcrete. He is a consulting engineer with over 40 years of experience on projects around the world.

**Abstract:** Wet-mix fiber reinforced shotcrete (FRS) is being widely used for ground support in civil tunnels and mining projects across North America. Quality Control of FRS production and application is of great importance to the owner, contractor and supplier. A typical quality control program includes: mix qualification, nozzlemen/equipment qualification, construction inspection and testing, dealing with any non-conformances and remediation of any defective shotcrete. A project example with project data is provided and discussed. Implementation of a proper quality control program is critical for shotcrete to meet the specified performance requirements, save costs, and improve safety.

## 1.0 Introduction

During the past several decades, fiber reinforced shotcrete is increasingly being used in ground support in civil tunnels, mines and other large infrastructure projects across the US and Canada. Recent technology advances include: new types of fibers, new supplementary cementitious materials, new accelerator products and advances in equipment such as robotic sprayers. Although there is still a large amount of dry-mix shotcrete being used for some projects, wet-mix fiber reinforced shotcrete now dominates the industry. During the project development stage, the owner needs to define the quality required for the shotcrete. The contractor needs to establish, execute, and implement a valid quality control program to meet the owner's requirements. This paper provides a general overview for the development of a suitable quality management program for wet-mix fiber reinforced shotcrete for ground support in civil tunnel and mining applications. Experiences and lesson learned from certain projects are discussed as these will help both the owner and the contractor understand and agree upon a suitable quality control program for a specific project.

For shotcrete construction, a proper quality management program is critical to ensure a successful project. In North America, a quality management program consists of two parts:

Quality Assurance (QA): QA refers to those planned systematic actions necessary to assure that the final product will perform its intended function (Ref. 1). QA starts with a project specification, design, construction drawings, and preparation of contract bid documents. The project owner and its representative, normally the engineer, are responsible for development and implementation of the QA program.

Quality Control (QC): QC includes physical characteristics of the materials, shotcrete processes and services which provide a means to measure and control the characteristics to predetermined quality standards or criteria (Ref. 1). The contractor is responsible for the QC program. An independent testing laboratory and/or shotcrete consultant are normally retained by the contractor to conduct QC testing and inspection.

## 2.0 Specification

The shotcrete specification is 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.F-2009 "Guide for Specifying Underground Shotcrete"
ACI 506.2-2013, "Specification for Materials, Proportioning and Application of Shotcrete"

ACI 506 R-2005, “Guide to Shotcrete”
AASHTO “Guide Specification for Shotcrete Repair of Highway Bridges”
These guides and specifications, together with other related documents from ACI, CSA, AASHTO and the US Army and Corps Engineer provide the basis for development of a suitable QA/QC program.

A typical shotcrete specification includes the following sections:
Scope
Definitions
Standards and codes
Materials
Shotcrete proportioning and performance requirements
Submittals
Preconstruction trial
Batching, mixing and supply
Shotcrete placing equipment and auxiliary equipment
Nozzleman qualification
Surface preparation
Reinforcement
Finish tolerance and thickness control
Safety
Shotcrete application
Curing and protection
Quality control inspection and testing
Shotcrete acceptance/rejection
Remedial measures
Clean-up
Quality measurement and payment

An example of typical shotcrete performance requirements is listed in Table 1.

**Table 1: Typical Shotcrete Performance Requirements (Ref 2)**

| Test Method | Property | Performance Requirement |
|---|---|---|
| - | Maximum water/cementing materials ratio | 0.42 |
| - | Temperature (at discharge into pump) | 10-30$^{o}$C |
| CSA A23.2-4C | Air content – as shot | 2.5-5.5 % |
| Penetrometer calibrated against end beams | Minimum early age compressive strength before re-entry under shotcrete | 2 MPa (290 psi) |
| ASTM C1604 &<br>CSA A23.2 – 14C | Minimum compressive strength of shotcrete cores at 28 Days | 35 MPa (5000 psi) |
| ASTM C642 | Maximum value of boiled absorption<br>Maximum volume of permeable voids | 8 %<br>17% |
| ASTM C1550 | Minimum energy absorption at 40 mm deflection in round panel test - Joules | 320 Joules |
| ASTM C1609 | Flexural strength at 7 days | 4 MPa (580 psi) |
| ASTM C1609 | Flexural toughness at 7 days | Toughness Performance Level III or IV |

### 3.0 Qualification of the shotcrete mixture, Preconstruction mock up shoot

Development of a suitable wet-mix FRS mixture design is one of the most important steps for a successful project. A suitable mixture must be simple for the contractor to work with and must meet the project specification requirements. For a wet-mix fiber reinforced shotcrete project for underground support, in addition to the performance requirements listed in Table 1, there is often a requirement for set time. A typical set time specification requires:

Initial set: less than 10 minutes
Final set: less than 45 minutes

The set time is dependent on cement type, finess of cement particles, use and replacement percentage of supplementary cementitious materials (SCMs) and most importantly, type and dosage of accelerator.
*Cement type*: CSA Type GU, or ASTM Type I/II are the most widely used cements in Canada and the US respectively. The set time for Type GU cement, when used with a suitable type and dosage of accelerator, is typically able to meet the set time requirements.
In California, a Type V cement is sometimes used instead of a Type I/II cement. The reason for this is that the soil often contains a high percentage of sulphate, and the Type V cement is high sulphate resistant and therefore can mitigate sulphate attack. It is further required to use a low water:cement ratio shotcrete when Type V cement is used. The challenge of using Type V cement in shotcdrete is that it is a slower setting cement since it contains a lower $C_3A$ content ($C_3A$ content is lower than 5%).
The use of *supplementary cementitous materials (SCMs)* can also increase the set time depending on the addition rate. High addition rates of fly ash, 25% and above, will result in slower set times. CSA limestone Portland Cement (Type GUL) also has slower set time. Therefore, the selection of the cement type is of importance.
*Cement finess* also affects the set time. Cement particles have typically been ground finer during the past several decades, and this has reduced set time.

## 4.0 Type and dosage of accelerator

The accelerator type and dosage are the single most important factors affecting the set time in wet-mix shotcrete. Currently, so-called alkali-free accelerators, based on Aluminum Sulphate are the most widely used accelerators in the tunneling and mining industries. With a dosage of 4-6% by mass of cement, such accelerator is typically able to achieve the required set time.
The problem most commonly encountered with accelerator usage is the accelerator dosing system. Currently, some of the accelerator dosing pumps are found to not reliably provide a constant flow of the accelerator during shotcrete application. This is largely due to the impulse system used in the accelerator dosing pump. The impulse rate is affected by the pump stroke rate, pressure, and the sensor in the dosing pump itself. For any dosing pump used in the shotcrete, it must be properly calibrated and verified. Ref. 3 provides a means of doing this.

## 5.0 Early age compressive strength development

One of the most important properties in using shotcrete for underground support is its early age compressive strength development. With proper mixture design and dosage of set accelerator, shotcrete can develop acceptable compressive strength in as early as 1 hour. The early age strength is able to provide immediate support to the ground and prevent shotcrete fall off. A typical guideline for the early age compressive strength development is provided in the Austrian J1-J2-J3 chart.

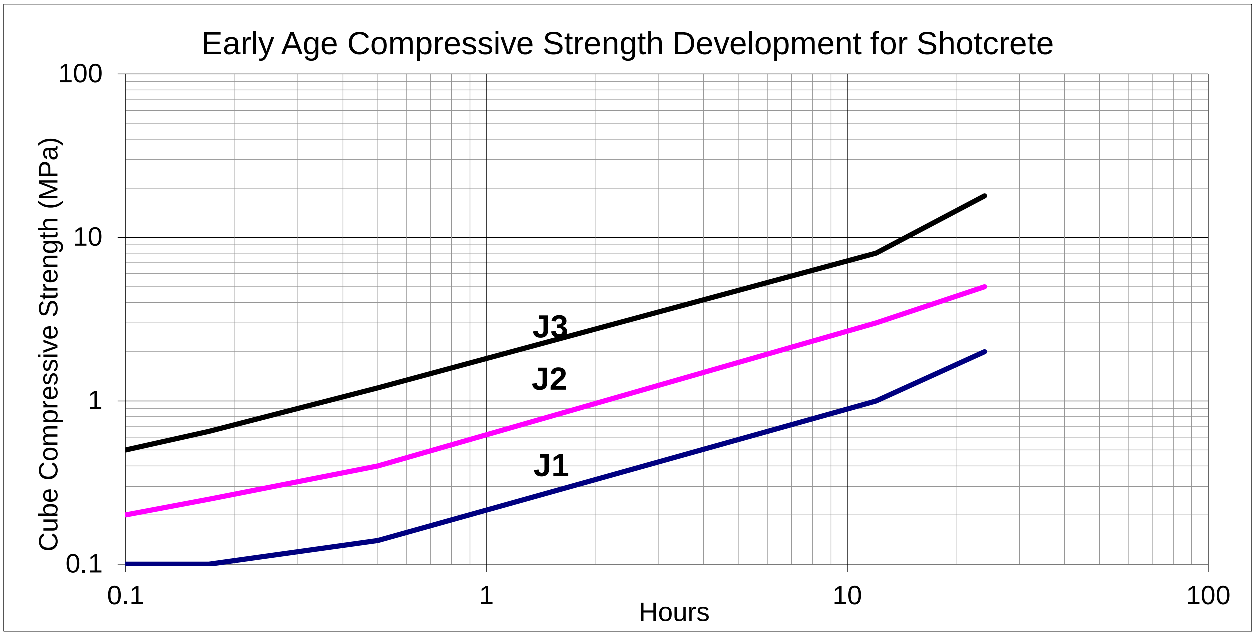

**Fig. 1 Early-age shotcrete development (Austrian Concrete Society Sprayed Concrete Guidelines)**

Early age compressive strength following the J2-curve is considered the most acceptable performance criteria for ground support in most tunneling/mining applications. In the J2-curve, the early age strength is required to be 0.5 MPa at 1 hr and 1 MPa at 2 hrs. In North America, it is generally accepted that 1 MPa is required before allowing manpower re-entry for most ground support.

In the mining industry, a mine "reentry time" is commonly used and it refers to the time when miners, or crews can come back to the ground supported by shotcrete, to conduct construction activities, such as drilling, anchoring, mucking and blasting. However, this concept is sometimes misunderstood. The mine re-entry time refers to the time when the shotcrete has developed sufficient strength, such as following the J2 curve, rather than a specific time of 1 hr or 2 hrs. The authors have interacted with miners, contractors, or owners took for granted that their crew members could enter shotcrete supported ground at half an hour or at one hour without knowing the actual early age strength development at that time. This poses a risk to workers' safety. To avoid this, the early age compressive strength development should be established by conducting a trial shotcrete application prior to the project and routinely monitoring early age compressive strength development during the project.

The effect of accelerator is dependent on both the shotcrete temperature and the temperature of the environment. During summer, the ambient temperature can be 15-30 C and above, which helps the accelerator to develop sufficient early age strength. Therefore, the early age compressive strength development tends to meet J2 requirements with only moderate accelerator dosage. During winter time, the ambient temperature is often 10-15 C and below, and it is typically found that the early age compressive strength development is slow unless the shotcrete temperature and accelerator dosage are increased. Therefore, it is recommended to conduct trial shotcrete testing in both warm weather and cold weather to establish the proper correlation between the reentry time and early age compressive strength.

## 6.0 Testing early age compressive strength

Although there are a number of different test methods available for early age strength testing and evaluation, the most reliable test method is the end beam test method (Ref. 4 & 5). This method tests a portion of a beam and provides a direct measure of compressive strength. During cold weather shotcrete trials, it is found that the end beams need to be protected so that the early age strength development is not adversely affected by the smaller test specimen size that might not generate as much heat to hydrate the cement as the in-place shotcrete lining. The end beam testing method is the most widely used test method in North America to determine the early age compressive strength development. The needle penetrometer is also sometimes used to test compressive strength for up to 1 MPa. This method is found to have greater variability and needs to be calibrated against the end beam testing method.

## 7.0 Flexural toughness and fiber reinforced shotcrete

One of the most successful advances in shotcrete technology in North America is the use of fiber reinforced shotcrete. Since the first application of steel fibers in shotcrete in 1970s, the technology has advanced each decade. Currently, macrosynthetic fiber and steel fiber are both widely used in wet-mix shotcrete in North America. They are used to replace, either partially or completely, the steel mesh in the ground support, reduce the construction cycle time and provide overall better performance in ground support. The combination of fiber reinforced shotcrete with a suitably designed rock anchor system is one of the most efficient ground support systems in many mines and civil tunnels.

Although there are different theories about ground support with fiber reinforced shotcrete lining systems, the most significant property of fiber reinforced shotcrete is the energy absorbed after shotcrete cracks, i.e., the flexural toughness. After shotcrete cracks, fibers are pulled out or fractured during the process of cracking, thereby redistributing and controlling crack propagation as the FRS lining system experiences deformation. The load bearing capacity of cracked FRS determines the performance of the lining system. In civil tunnels, the deformation is often required to be less than 5 milimeters, but in mines, the deformation is often allowed to be much larger, with deformations as large as 50 mm or even higher. This requires high performance fiber reinforced shotcrete to be able to withstand the induced load at such high deformations.

Design of the FRS is commonly based on performance based design methods which utilize flexural toughness testing results. Typical flexural toughness test methods include:
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-fibre-reinforced-concrete (notched beam test)
BS EN 14651 Test for metallic fiber concrete – measuring the flexural tensile strength (notched beam test)
BS EN 14488-5-2006 Testing sprayed concrete - Determination of energy absorption capacity of fibre reinforced slab specimens

The flexural toughness, the residual strength and the peak load (peak strength) are the most important factors to evaluate the performance of fiber reinforced shotcrete.
In North America, there are two typical project specifications for flexural toughness performance requirements for FRS:

### # 1 Toughness performance level (TPL) based on ASTM C1609 test method (Ref. 6 & 7)

When TPL is specified, it requires the shotcrete test panel to be cut into beams with dimensions of 100x100x350 mm, and tested to ASTM C1609. If the TPL meets the Toughness Performance Level III, it meets the general support requirement for most ground conditions.

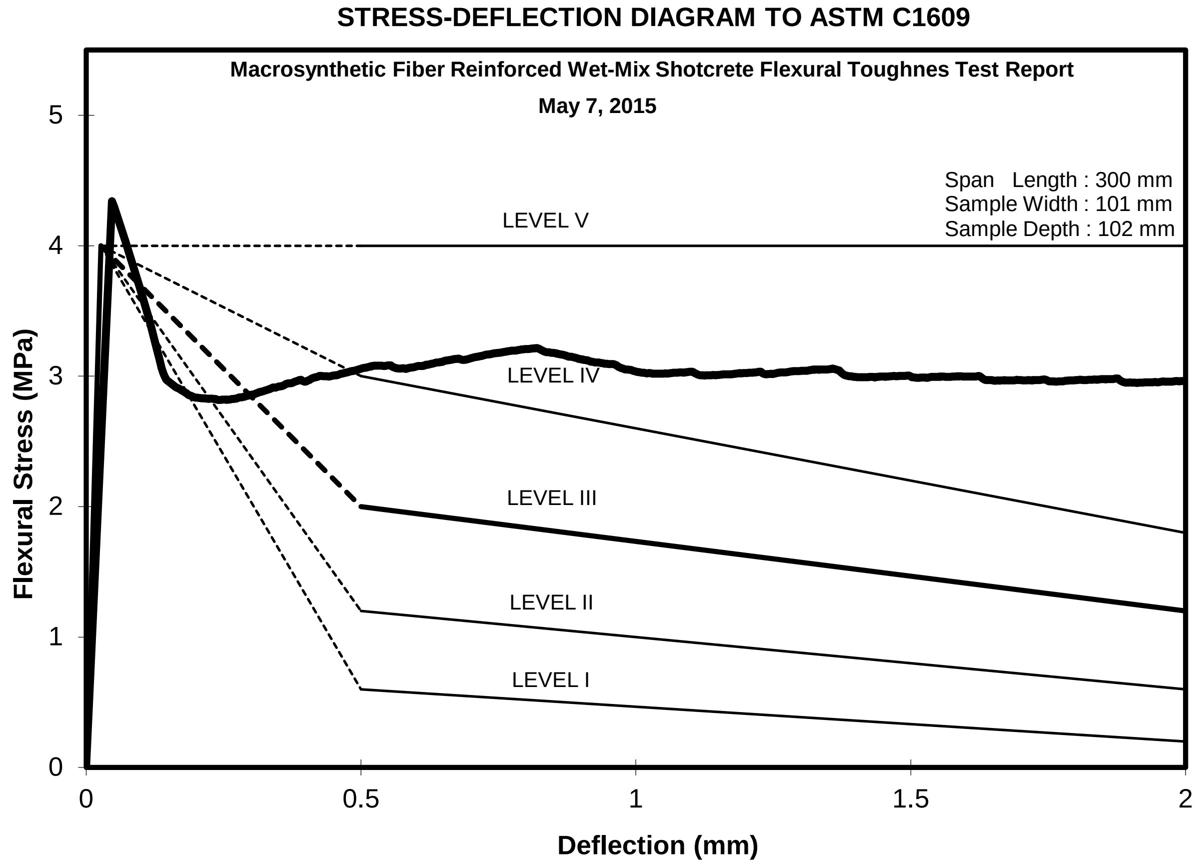

**Fig. 2 Toughness Performance Level (TPL) for macro-synthetic fiber reinforced wet-mix shotcrete**

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

When the RDP method is specified, it requires samples of round determinate panel (RDP) to be shot with dimensions of 800 mm in diameter and 75 mm in thickness. The RDPs are tested to ASTM C1550 and the total energy absorbed up to 40 mm deflection is reported.

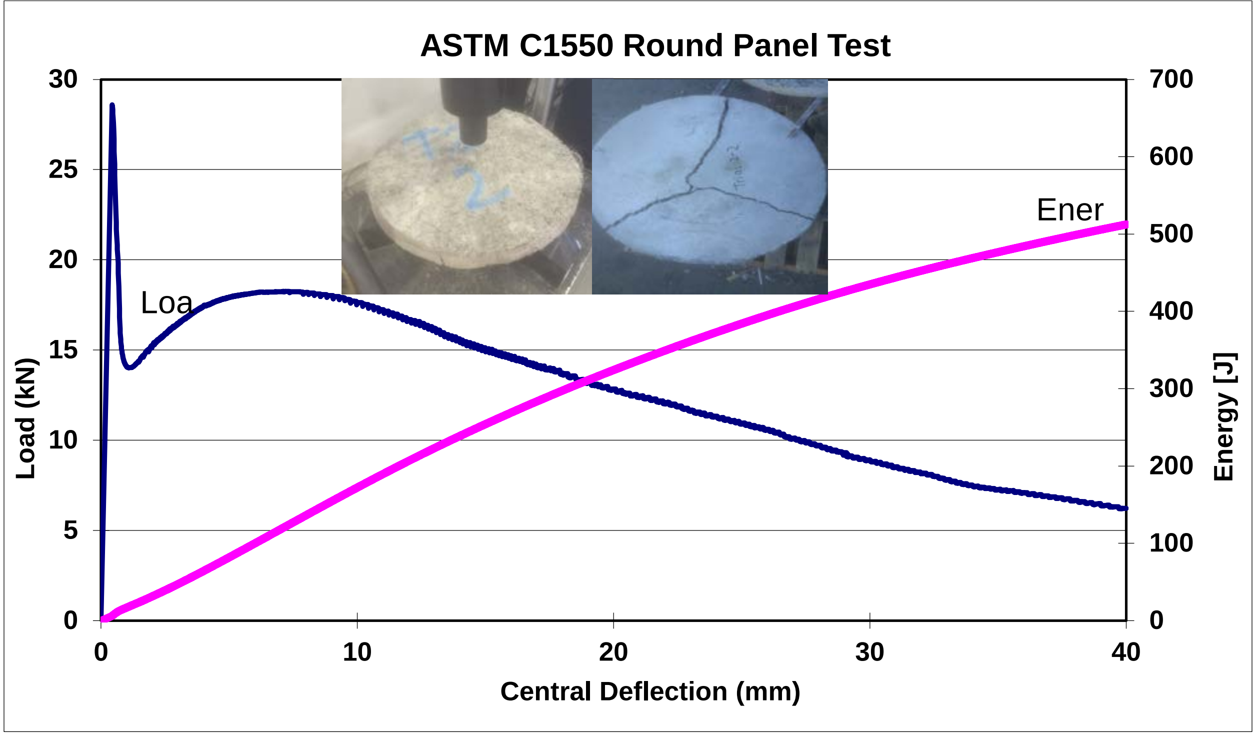

**Fig. 3 ASTM C1550 Round Determinate Panel Flexural Toughness test result**

A typical specification requirement for flexural toughness based on RDP is listed as follows:

**Table 2. An example of specified flexural toughness based on ASTM C1550 Round Panel Test**

| Age of Shotcrete from Time of Batching | Average Energy Absorption (ASTM C1550) | Deflection |
|---|---|---|
| 3 days | 250 Joules | 40 mm |
| 7 days | 350 Joules | 40 mm |
| 28 days | 450 Joules | 40 mm |

Both the TPL and the RDP methods are applicable to both steel fiber and macrosynethic fiber. Both tests require the use of a closed-loop testing machine to accurately test the fiber flexural performance (Ref 8 & 9). When accelerator is used in wet-mix shotcrete, the flexural toughness increases substantially at early ages, such as 1-3 days, but does not increase much from 7 to 28 days. On the contrary, if the compressive strength of the shotcrete exceeds 50 MPa, the flexural toughness could decrease from 7 days to 28 days due to the increased brittleness of the shotcrete matrix.

When both fibers and accelerators are used in wet-mix shotcrete, a pre-construction shotcrete trial must be conducted to verify that the shotcrete mixture meets the specified performance requirements for set time, early and later age compressive strength development and flexural toughness.

## 8.0 Qualification of the shotcrete nozzlemen, pre-construction nozzlemen qualification trial shoot

After the shotcrete mixture is qualified, the shotcrete nozzlemen need to be qualified. This requires the nozzlemen to properly apply shotcrete to the receiving surface. More specifically, the qualification of the shotcrete nozzlemen requires:

1) Nozzlemen needs to understand the basics of concrete and shotcrete technology. This includes how the cement hydrates, including temperature effects on shotcrete and the effects of accelerator and other chemical admixtures on shotcrete performance.
2) Workability, pumpability and shootability. The nozzlemen should understand that the slump, or consistency of the shotcrete mixture is critical for transport, pumping and shooting and that overhead application and vertical application pose different challenges for shotcrete application.
3) Preparation of the substrate, including cleanness and roughness and that the receiving surface moisture condition should be saturated surface dry (SSD) to achieve optimized bond.
4) Proper calibration of accelerator dosing pump.
5) How to build up shotcrete overhead and vertical thickness properly.
6) Proper control of nozzle angle, distance, shooting pattern to minimize rebound and overspray.
7) Proper procedure to apply thicker layers of shotcrete. Multi-layer shotcreting.
8) If shotcrete falls off, either from overhead or vertical surfaces, the nozzlemen should be able to determine immediately what is being done wrong and how to make the necessary corrections.

The nozzlemen qualification program is essential to a successful project as it:

- Educates the nozzlemen on shotcrete materials, equipment, concrete technology and use 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. An example is a section of the reinforcement (Figs. 4 & 5), and a segment of a tunnel support. (Fig. 6)

**Fig. 4 Test panel set up for nozzleman qualification shooting for a section of lattice girder**

**Fig. 5 Nozzleman qualification shooting with FRS for a section of lattice girder.** Note that robotic sprayer shot macrosyntehtic fiber reinforced wet-mix with 6% accelerator. Cores show shotcrete consolidated properly around the reinforcement.

**Fig. 6 Nozzleman qualification shooting at a segment in a tunnel. In-situ cores were extracted and visually assessed.**

In North America, nozzlemen who operate the nozzle by hand are required to be certified by the American Concrete Institute (ACI) (Ref. 10). Prior to take the certification exam, they normally take a one day training class provided by the American Shotcrete Association (ASA). To become an ACI certified nozzleman, they must pass the written exam, and the performance exam. Everyone is required to shoot a test panel with reinforcement, and five cores are extracted to evaluate the shotcrete consolidation around the reinforcement. Detailed information can be found in www.shotcrete.org. The hand nozzle technique not only helps the nozzleman understand how to properly apply shotcrete, but also helps them to develop proper shooting technique when operating a robotic sprayer. Compared to hand nozzlling, the robotic sprayer is more robust and requires higher skills to operate. Equipment suppliers typically provide training on how to operate the robotic sprayer.

During a recently completed tunnel project in BC, Canada, over 5000 $m^3$ of wet-mix shotcrete was applied to two 7 km long tunnels. The nozzlemen qualification program included three components:

Level 1: ACI certification. Only ACI certified shotcrete nozzlemen were allowed to work on the project. All nozzlemen were required to shoot standard American Concrete Institute (ACI) test panels in both vertical and overhead orientations with wet-mix shotcrete using hand nozzling. Five cores were extracted and examined by the ACI nozzlemen examiner and compared to ACI C660 CP60 requirements. Fig 7 shows the ACI overhead panel for shooting by the nozzlemen.

**Fig. 7 ACI nozzlemen examination panel for overhead shooting**

Level 2: Qualification panel shooting and testing. Mesh reinforced test panels were shot and cores were extracted to test the shotcrete for compressive strength, boiled absorption and volume of permeable voids for each nozzlemen for both vertical and overhead orientations. Fig 8 shows a nozzleman shooting an overhead panel.

**Fig. 8 Qualification panel for overhead shooting**

Level 3: In-situ qualification shooting & Testing. Several testing areas were selected by the design engineer to qualify the mock-up shooting for each nozzlemen. The most challenging area for shotcrete application was selected for the qualification test for each nozzlemen. In-situ cores were then extracted and tested for compressive strength, boiled absorption and volume of permeable voids to qualify each nozzlemen. Fig. 9 shows a nozzleman shooting for in-situ qualification for the most challenging ground support condition.

**Fig. 9 In-situ mock up qualification shooting**

Over the shotcrete construction period of 4 years, a total of over 40 nozzlemen participated qualification program but ONLY less than 10 nozzlemen were qualified for shotcrete application and they carried out the shotcrete work for the tunnel. The rigorous qualification program provided a safe work environment, and no shotcrete related accidents or incidents occurred during the construction period.

## 9.0 Construction Inspection & Testing Plan (ITP)

### 9.1 Inspection

During the shotcrete construction stage, a quality control testing and inspection plan should be established and executed. For civil tunnel projects, field inspection is normally conducted full time by the design engineer appointed by the project owner, or may be conducted by a shotcrete consultant appointed by the contractor. The field inspection is intended to make sure that shotcrete is applied as per the specification requirements, including thickness and control over overspray and rebound. This can be a challenge for the project owner as there is a shortage of qualified inspectors. A qualified inspector could be an engineer, technologist, consultant, or a nozzleman and must have a basic understanding of underground shotcrete construction. Currently, the American Concrete Institute is developing a shotcrete inspector program and intends to certify the shotcrete inspector.

### 9.2 QC testing for fresh shotcrete

The plastic properties of shotcrete requires testing the slump, air content and temperature. The slump for fiber reinforced shotcrete for civil tunnels and mines is tested with a slump cone and is normally required to be in the range of 150-200 mm, with a few projects requiring higher slump.

The air content test follows the ASTM C231 - 14 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method. Both as-batched air content and as-shot air content are normally required to be tested. As –batched air content refers to the air content in the ready mix wet-mix shotcrete. Samples are normally taken at the point of discharge from the ready mix truck into the shotcrete pump. As-shot air content refers to the air content after the shotcrete has been applied. Samples are normally taken either from the shotcrete on the wall, or the shotcrete is directly applied into the air meter base. This is easily done with regular shotcrete but can be challenging with rapidly setting accelerated shotcrete.

As-shot air content is of importance as it represents the actual air content in the shotcrete. The air content is important for freeze thaw durability requirements. Entraining sufficient air by adding an air entraining agent is one of the most efficient ways to mitigate the damaging effects of cycles of freezing and thawing. Entraining air into shotcrete has many benefits, including improved pumpability, a slump killing effect on shooting (Ref. 11), and most importantly, an increase in freeze-thaw durability. With addition of an air entraining agent, the as-batched air content is normally 7-10 %. After the shooting, about half the entrained air is knocked out by the compaction process and the as-shot air content is normally 2.5-5.5%. Although this is lower than the required air content for concrete to be able to resist freeze-thaw attack, it has been shown that the air voids system does provide satisfactory freeze-thaw durability resistance for properly applied shotcrete (Ref. 12).

## 9.3 QC testing for hardened shotcrete

Quality control tests for hardened FRS normally require measurement of compressive strength, boiled absorption and volume of permeable voids, and flexural toughness at a specified frequency (Ref. 13).

Compressive strength for cores extracted from test panels at a certain frequency, such as one set of three cores for every 200 $m^2$ of shotcrete, or every 40 $m^3$ shotcrete. Three cores are tested at 7 days and three cores are tested at 28 days.

Boiled absorption and volume of permeable voids

1 set of three cores for every 200 $m^2$ of shotcrete, or every 40 $m^3$ shotcrete, tested at 7 days.

Flexural toughness

1 set of round panels for every 500 $m^2$ of shotcrete, or every 100 $m^3$ shotcrete tested to ASTM C1550 at 7 days, or
1 set of beams for for every 500 $m^2$ of shotcrete, or every 100 $m^3$ shotcrete tested to ASTM C1609 at 7 days.

## 9.4 Sample extraction and Testing

Although shotcrete test panels are the most common source for cores, beams and round panels, in-situ core samples can also be extracted for compressive strength and boiled absorption testing. The in-situ core samples represent the actual shotcrete in the lining. They can be used to determine the thickness of shotcrete, and for visual assessment of the bond between shotcrete and substrate rock.

In-situ sample extraction (Fig. 10) is required if the test results from standard shotcrete test panels do not meet the specification requirements. Should test results from the shotcrete test panels fail to meet the specification requirements, while the in-situ cores meet the specification, shotcrete should be accepted.

**Fig. 10 Core hole from in-situ core extraction**

## 9.5 QC results analysis

The QC test frequency is normally required to be most frequent at the start of the project, and may be reduced if the QC test results consistently meet the project specification. The QC results should be analyzed by the consultant or engineer to understand the general quality of the shotcrete. In particular, the compressive strength results should be statistically analyzed on a weekly or monthly basis. Abnormal test results must be analyzed and discussed with the project team. (Ref. 14 & 15)

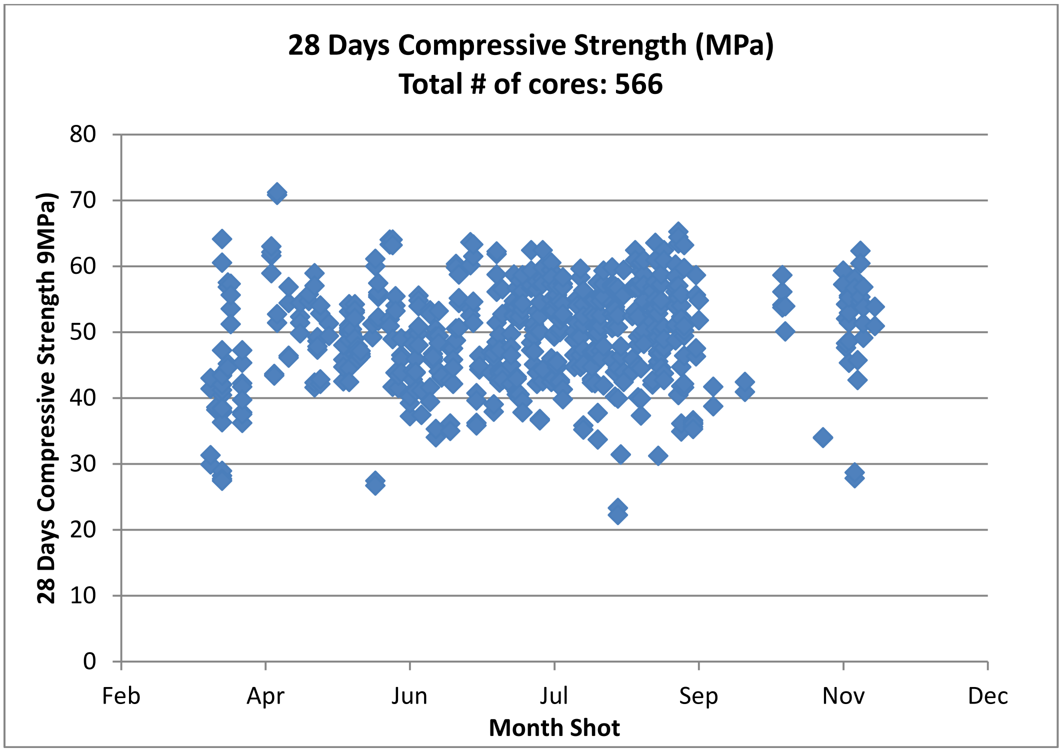

**Fig. 11 Statistical Analysis for compressive strength**

Fig. 11 shows a data set for 28 day compressive strength for 566 cores from one tunneling project. It provides a good indication of the type of variability that can be expected on a shotcrete tunnel lining project.

### 9.6 Non-conformance & remediation of defective shotcrete

If defective shotcrete is identified by QC testing and inspection, the shotcrete should be removed and replaced. The best way to avoid this is to implement the recommendations for a proper QA/QC plan as described in this report. Fig. 12 below shows an example of defective shotcrete in which an improperly operating accelerator dispensing system resulted in layers of shotcrete overdosed with accelerator which seriously negatively affected the shotcrete application and quality.

**Fig.12 Defective macrosynthetic fiber reinforced wet-mix shotcrete (with accelerator) beams, layers of pockets and voids show over dosed accelerator.**

## 10.0 Conclusions

Fiber reinforced shotcrete (FRS) has been established as an effective method for ground support. Development of a proper quality management plan with a suitable quality assurance and quality control program are essential for a successful project.

Both steel fiber and macro synthetic fiber are able to provide sufficient flexural toughness for shotcrete linings for many tunnelling and mining projects. The required performance characteristics of the FRS should be determined by the design Engineer/Owner together with establishment of a proper quality control program.

A proper FRS quality control program is one of the most important factors in achieving a successful project. It requires mixture qualification, nozzleman qualification, quality control testing and inspection, and remediation of any non-conforming shotcrete.

Either beam testing to ASTM C1609 or round panel testing to ASTM C1550 is able to evaluate FRS flexural toughness performance. Project experience in FRS quality control testing in the US and Canada provides a substantial database for performance in shotcrete tunnel lining. This data can be useful in the selection of FRS for future projects, including selection of fiber types and addition rates.

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