Tunnel Shotcrete Lining for Hydroelectric Projects

British Columbia, Canada

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In British Columbia (BC), Canada, the primary source of power supply is hydroelectricity. The BC government, through its Crown corporation, BC Hydro, has worked with private-sector companies to provide sustainable and renewable energy. As a result, private-sector companies are building hydroelectric projects throughout the province of BC. One such company, Innergex, built two hydroelectric projects: one in the Upper Lillooet area, about 150 miles (250 km) north of Vancouver and 50 miles (80 km) north of Whistler, and the other in the Big Silver area, which is about 150 miles east of Vancouver and 30 miles (50 km) north of Harrison Lake. All of these tunnels are in hard rock and have been constructed by the drill-and-blast method with rock bolts and fiber-reinforced shotcrete lining. At the start of the projects, dry-mix shotcrete was used based on the contractor's previous underground project experience. Soon after the start, wet-mix shotcrete was introduced as an alternative method. The contractor was impressed with wet-mix shotcrete's productivity and performance along with its major dust reduction and safety aspects. As a result, wet-mix was adopted as the primary shotcrete placement method. With increased productivity using wet-mix, the construction schedule was significantly reduced, resulting in substantial cost savings. Of note, dry-mix shotcrete continued to be used for special ground conditions. Specifically, dry-mix shotcrete was very useful in very wet conditions where the water could not be easily controlled using drainage pipes. Dry-mix shotcrete allowed the contractor to seal off the area while completing the installation of drainage pipes.

The wet-mix shotcrete was initially reinforced with wire mesh and applied by remote control robotic sprayer. Shortly after, the tunnel lining method was changed to use macrosynthetic fiber-reinforced wet-mix shotcrete. A silica-fume-modified shotcrete mixture was designed and then shot in a trial application. Test results met the project specification requirements for tunnel construction. Wet-mix macrosynthetic fiber-reinforced shotcrete placed between October 2014 and September 2015 used prebagged materials supplied from Vancouver and mixed with water on site. The contractor then set up a concrete batch plant on site and started producing shotcrete using local aggregates. The shotcrete mixture was qualified for use on the project by testing for compressive strength, boiled absorption, and volume of permeable voids to ASTM C642, and flexural toughness based on use of the round circularly loaded panel to ASTM C1550. The effect on shotcrete performance using different addition rates of alkali-free accelerator was tested in trial shooting. An addition rate of 6% alkali-free accelerator by mass of cement was selected.

Shotcrete nozzlemen were trained with a specially designed shotcrete training program. All shotcrete nozzlemen were qualified to shoot a basic Level I for shotcrete without reinforcing steel, and a more challenging Level II, for shotcrete with reinforcing steel or lattice girders. The construction quality control test results for all three tunnels from August 2014 to December 2016 demonstrated that the shotcrete quality consistently met the project specification requirements. The projects were completed on schedule because of productivity gains achieved from using wet-mix macrosynthetic fiber-reinforced shotcrete. The contractors used proper skills and techniques for application of wet-mix macrosynthetic fiber-reinforced shotcrete applied by robotic sprayers with zero safety incidents or accidents.

INTRODUCTION

For both the Upper Lillooet and the Big Silver projects, the drill and blast tunneling method was used. Depending on the ground conditions, the tunnel construction progress varied. The Big Silver Hydro Power project involved a tunnel 1.1 miles (1.8 km) long. The ground condition is primarily hard rock, and construction of the tunnel was completed within 5 months. For the Upper Lillooet project, two tunnels were built at the same time: the Boulder Creek tunnel and the Upper Lillooet tunnel. Project tunneling work started in June 2014 and was completed by October 2016.

During the tunneling construction of the Big Silver and Upper Lillooet projects, shotcrete was used as the primary lining support, and also served as the final lining. The Boulder Creek D-shape tunnel had dimensions of 12 x 15 ft (3.6 x 4.5 m) and total length of 9593 ft (2924 m), and a total volume of 2047 yd^3 (1565 m^3) of wet-mix shotcrete and 820 yd^3 (627 m^3) of dry-mix shotcrete were applied. The Upper Lillooet D-shaped tunnel had dimensions of 20 x 18 ft (6 x 5.5 m) and total length of 8399 ft (2560 m), and a total of 11,254 yd^3 (8604 m^3) of wet-mix shotcrete and 362 yd^3 (277 m^3) of dry-mix shotcrete were applied.

Fig. 1: Upstream tunnel portal for Upper Lillooet Hydroelectric project

Rock anchors and shotcrete were used as the primary ground support. This article focuses on technical aspects of the shotcrete used in the Upper Lillooet tunnel project.

SHOTCRETE SOLUTION

The project contractor, tunnel design engineer, and consulting engineer worked together to develop the shotcrete specification. Performance characteristics included:

- Minimum compressive strength: 1500 psi (10 MPa) at 3 days, 2900 psi (20 MPa) at 7 days, and 5100 psi (35 MPa) at 28 days;
- Boiled absorption to ASTM C642: maximum 8% at 7 days;
- Volume of permeable voids to ASTM C642: maximum 17% at 7 days;
- Flexural toughness based on ASTM C1550 Round Panel Test Method: 350 Joules at 7 days; and
- Shotcrete nozzlemen: nozzlemen must be prequalified to shoot the shotcrete.

SHOTCRETE MIXTURE

Dry-mix shotcrete was used in the tunnel at the beginning of the project. A total of three trial mixtures were shot and tested. The mixture with moderate early-age strength development was selected for production.

As the project proceeded, the contractor and consulting engineer entertained the idea of using the wet-mix shotcrete process. This was introduced to the project as a new approach because the contractor's project engineer and nozzlemen did not have much wet-mix shotcrete experience. The wet-mix shotcrete mixture design proposed for use is shown in Table 1.

Table 1: Wet-Mix Shotcrete Mixture Design

Material	Mass per m^3 (kg)
Cement Type GU	410
Silica fume	40
Coarse aggregate (10 to 5 mm, saturated surface dry (SSD))	430
Fine aggregate (SSD)	1320
Estimated water, L	185
High-range water-reducing admixture,[*] L	1.00
Macrosynthetic fiber	7.0
Hydration control admixture,[†] L	1.00
Air content (4.5 to 6.5%)	3.5
Total	2394

[*] Add high-range water-reducing admixture at dosage required to achieve the maximum allowable water-cementitious materials ratio (*w/cm*) ratio and required slump.

[†] Add hydration-controlling admixture if required to provide extended workability.

Note: Add alkali-free accelerator at nozzle at dosages to meet set time and early-age strength development requirement.

Performance Requirements	
Minimum compressive strength	10 MPa at 3 days, 15 MPa at 7 days, 35 MPa at 28 days
Boiled absorption	Maximum 8%
Volume of permeable voids	Maximum 17%
Slump	170±20 mm before accelerator addition
Maximum *w/cm*	0.45
Air content	2.5 to 5.5% by volume
Maximum size of aggregate	10 mm

Notes: 1 MPa = 145 psi; 25 mm = 1 in.

Fig. 2(a) and (b): On-site shotcrete batching; note that the batch plant and concrete truck were insulated for the cold weather

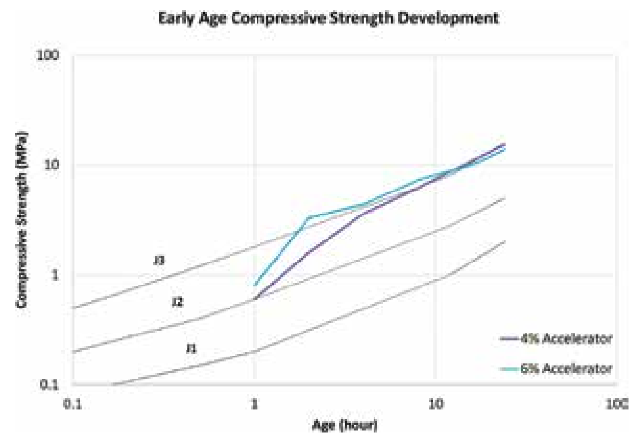

Fig. 3: Early-age compressive strength development

Table 2: Compressive Strength, MPa

Accelerator dosage (by mass of cement %)	3 days	7 days	28 days
4%	33.5	44.2	48.7
6%	23.3	30.2	39.3

Note: 1 MPa = 145 psi

PRECONSTRUCTION MOCKUP TRIAL SHOOT AND MIXTURE QUALIFICATION

Prior to the shotcrete application in the tunnel, the wet-mix shotcrete mixture was prequalified by a trial shoot in the field. Materials and equipment to be used for the tunnel construction were used for the prequalification shooting. An experienced nozzleman conducted the trial shoot. The trial shoot evaluated the batching, mixing, delivery, pumping, and placement characteristics of the shotcrete. Chemical admixtures were added and adjusted as needed. High-range water-reducing admixture was added to adjust the workability (slump) and hydration control admixture was added to control the slump retention time (also called *pot life* in the field). Alkali-free accelerator was added at the nozzle at two dosages to evaluate setting time and early-age compressive strength development. At a dosage rate of 0.2 gal./yd^3 (1 L/m^3), the hydration control admixture extended the slump retention time by about 1 to 1.5 hours. The slump retention time is also affected by the ambient temperature and radiant heat effects from the sun.

The early age (up to 24 hours) compressive strength data is plotted in Fig. 3. It shows that the shotcrete mixture with both 4 and 6% accelerator achieved the Austrian Guideline for Sprayed Concrete J2 level. An accelerator addition rate of 6% by mass of cement was selected for the shotcrete construction.

COMPRESSIVE STRENGTH

During the trial shoot, test panels were shot, and cores were extracted for compressive strength testing at 3, 7, and 28 days. Compressive strength test results are shown in Table 2. Table 2 shows the compressive strength for shotcrete with 4% accelerator is higher than the shotcrete with 6% accelerator at 3, 7, and 28 days. This shows that although the accelerator increases the early-age strength during the first 24 hours, the compressive strength for shotcrete with a higher accelerator dosage results in lower strength at 3, 7, and 28 days. These test results met the specified 35 MPa at 28 days requirement.

The boiled absorption (BA) and volume of permeable voids (VPV) test results (Table 3) are dependent on the accelerator dosage, nozzleman shooting technique,

Table 3: Boiled Absorption (BA) and Volume of Permeable Voids (VPV)

Volume of permeable voids (VPV)	Boiled absorption, %	Suggested quality indicator
<14	<6	Excellent
14 to 17	6 to 8	Good
17 to 19	8 to 9	Fair
>19	>9	Marginal

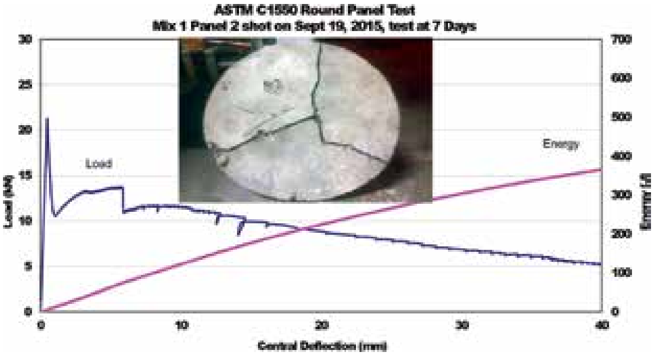

Fig. 4: Flexural toughness test result to ASTM C1550, round determinate panel test

overspray and rebound, and other factors. The BA and VPV values for 4% accelerator were 5% and 11%, respectively, and the BA and VPV values for 6% accelerator were 7% and 17%, respectively. The specified maximum allowable BA and VPV values were 8% and 17%, respectively. This is considered to be in the Good category in the quality indicator.[1]

FLEXURAL TOUGHNESS

Macrosynthetic fiber was used for the wet-mix shotcrete. Flexural toughness was tested using the ASTM C1550 round panel test method. Test results for three round panels averaged 372 Joules. Figure 4 shows a typical load-versus-deflection curve for the round panel test at 7 days.

SHOTCRETE EQUIPMENT

Wet-mix shotcrete was applied using a robotic sprayer rig provided by Putzmeister. The sprayer model was SPM 4210. This model operates electrically and includes an electric air compressor in the chassis. This robot has a variable pump flow between 5 and 26 yd^3/h (4 and 20 m^3/h). The required concrete pump flow is adjusted by the nozzleman using the robotic sprayer computer. Once calibrated, the accelerator dosage is adjusted automatically by the computer according to the concrete pump flow.

Dry-mix shotcrete was applied by hand nozzling application using an Aliva 252 dry-mix shotcrete machine.

NOZZLEMAN QUALIFICATION

The tunnel shotcrete lining required shotcrete application with a remote-controlled robotic sprayer. This sprayer provided a higher production rate and increased safety for the nozzleman. Operation of the robotic sprayer for placing quality shotcrete requires qualified nozzlemen. The project-specific shotcrete nozzleman qualification program was

Fig. 5: Putzmeister SPM 4210 robotic sprayer

Fig. 6: Robotic sprayer applied wet-mix shotcrete at the tunnel heading

Fig. 7: Hand-nozzling qualification for dry-mix shotcrete

custom-designed to give the nozzlemen shotcrete knowledge including:

1. Understanding the basics of concrete and shotcrete. This includes how cement hydrates and shotcrete temperature effects on the required dosage of accelerator and other chemicals;
2. Workability, pumpability, and shootability. Nozzlemen should understand that the slump (or consistency of the shotcrete mixture) is critical for transport, pumping, and shooting. Overhead application and vertical application pose different challenges for shotcrete application;
3. Preparation of the substrate, including cleanliness and roughness (surface moisture condition to achieve optimized bond);
4. Calibration of accelerator dosing pump;
5. Methods to build up overhead and vertical thickness properly;
6. Proper control of nozzle angle, distance, and shooting pattern to optimize shotcrete consolidation and minimize rebound and overspray;
7. Proper procedures for multilayer shotcrete application; and
8. If shotcrete falls off, from either overhead or vertical surfaces, nozzlemen should be able to immediately determine what is being done wrong and take the required corrective actions.

Two levels of shotcrete nozzlemen qualification were designed and implemented as follows:

Classroom seminar: A half-day classroom education session specifically targeted to the underground shotcrete application.

Level I Qualification: This was the basic level of qualification. Each nozzleman was required to shoot one vertical test panel and overhead test panel without reinforcement using the concrete mixtures and equipment on the project. This level was designed to qualify the nozzleman's basic shooting skills. The nozzleman was required to demonstrate proper use of accelerator; proper judgement of shotcrete slump; understanding of set properties; and safe operation procedures, including how to handle blockages. Cores were extracted for compressive strength testing at 3, 7, and 28 days and BA and VPV testing at 7 days.

Level II Qualification: Each nozzleman was required to operate the robotic sprayer to shoot one vertical mockup test panel and one overhead mockup test panel with reinforcement. Cores were extracted for visual inspection of the quality of shotcrete encapsulation of reinforcement. The reinforcement selected in the project qualification program was a section of lattice girder.

During the Level I and Level II qualification shooting, both fiber-reinforced wet-mix shotcrete (FRS) and dry-mix shotcrete were used.

Figure 8 shows nozzleman qualification shooting with FRS for a section of lattice girder. Note that the robotic sprayer shot macrosynthetic FRS with 6% accelerator. Cores show shotcrete properly consolidated around the reinforcement.

With more than 20 nozzlemen candidates on the project, the qualification program proved quite challenging. These nozzleman candidates came from different sectors of the shotcrete industry and most of them had more than 5 years of shotcrete experience. Some of them had been certified for hand nozzling by the American Concrete Institute (ACI). A total of 16 nozzlemen were qualified for both Level I and Level II qualifications and they worked in shifts on the projects. The rigorous shotcrete nozzleman qualification program ensured that quality shotcrete was placed during the construction stage. No shotcrete-related accidents or incidents occurred during the projects.

SHOTCRETE QC TESTING AND STRENGTH TEST RESULTS

Shotcrete test panels were shot for every day of shotcrete application or every 65 yd^3 (50 m^3), whichever came first. Cores were extracted for testing at 3, 7, and 28 days for compressive strength. If the test panel core strength did not meet the specified strength, cores were extracted from the in-place tunnel lining to verify the compressive strength. If the in-place shotcrete strength did not meet the specified

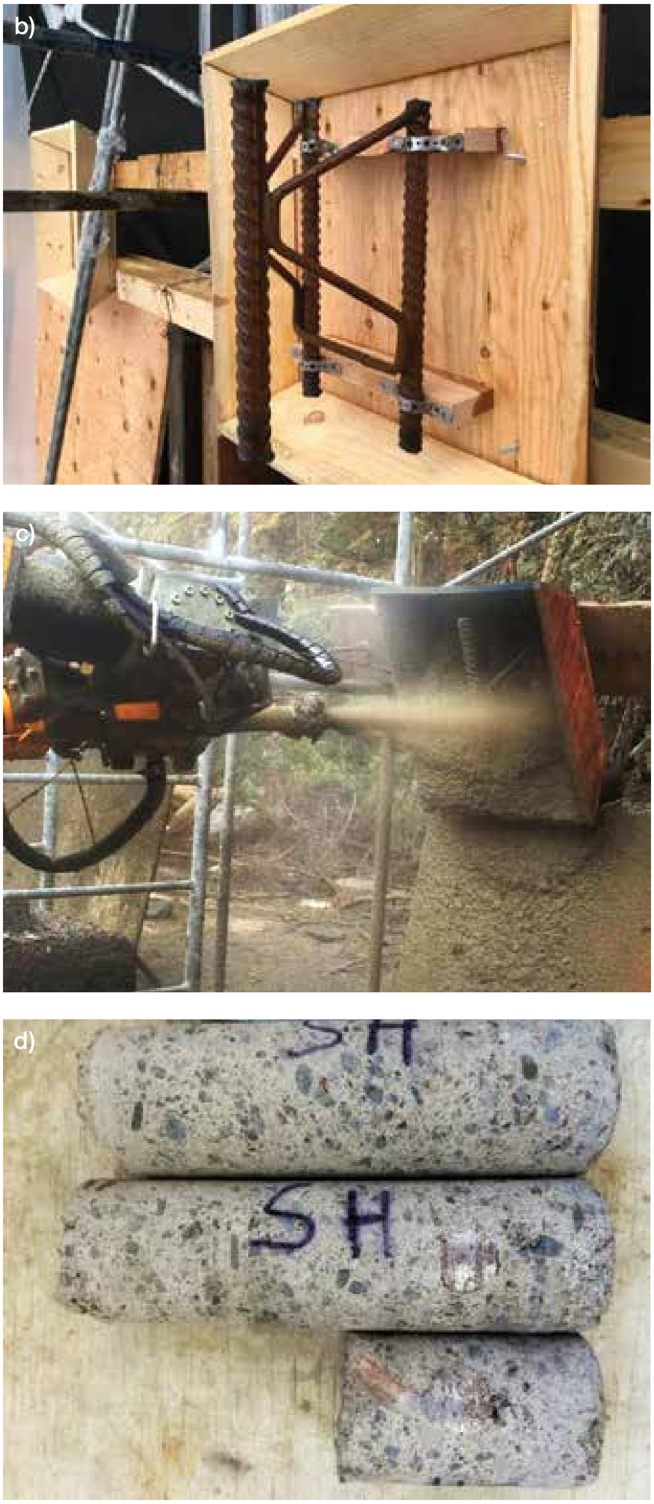

Fig. 8(a), (b), (c), and (d): Nozzleman qualification shooting and core evaluation

Table 4: Compressive Strength of Shotcrete During Construction Stage

Year	No. of cores	Average compressive strength, MPa	Standard deviation	% of Design strength
		3 days		
2014	45	24.2	5.3	242
2015	16	32.2	9.8	322
2016	19	21.2	3.8	212
Average	80	24.9	7.2	249
		7 days		
2014	68	30.5	4.7	203
2015	19	31.7	7.1	211
2016	105	31.2	5.7	208
Average	192	31.0	5.5	207
		28 days		
2014	70	40.2	6.7	115
2015	19	44.5	6.8	127
2016	107	48.9	6.8	140
Average	196	45.2	7.9	129

Note: 1 MPa = 145 psi

strength, then the shotcrete was considered deficient and would be required to be removed and replaced. During the project construction stage, some quality test panels did not meet the specified compressive strength. Cores were extracted from the in-place shotcrete lining and tested. They all met the specified compressive strength requirements so no removal and replacement was required.

Table 4 summarizes the shotcrete core compressive strength test results from the Upper Lillooet project during the project stage. Compressive strength is, on average, 3610 psi (24.9 MPa) at 3 days, 4500 psi (31.0 MPa) at 7 days, and 6560 psi (45.2 MPa) at 28 days. This readily satisfied the specified minimum compressive strength requirements.

CONCLUSIONS

The projects started using the dry-mix shotcrete application process exclusively, but shortly switched to using wet-mix shotcrete as the primary process. Wet-mix shotcrete provided major advantages in the production rate and allowed the project to meet the rapid construction schedule required for tunneling advancement.

A properly designed preconstruction trial shooting program qualified the shotcrete mixture, equipment, nozzlemen, and the shotcrete production system. The rigorous shotcrete nozzleman qualification program ensured the installation of quality shotcrete during construction. No shotcrete-related accidents or incidents occurred.

In summary, the use of wet-mix macrosynthetic fiber-reinforced shotcrete applied by remotely controlled nozzle equipment proved to be an effective and economical means of tunnel lining. It provided safety and productivity in tunnel advancement.

References

1. Ripley, B.D.; Rapp, P.A.; and Morgan, D.R., "Shotcrete, Construction and Quality Assurance for the Stave Falls Tunnels," *Canadian Tunneling*, 1988, pp. 141-156.

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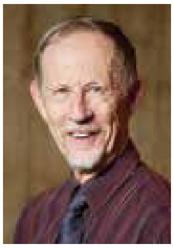

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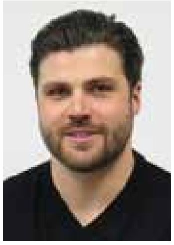

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