Shaft Lining with Dry-Mix Shotcrete

By Lihe (John) Zhang, D.R. (Rusty) Morgan, Ted Walter, Brian McInnes, Andrew Rule, and Allen Mitchell

The Greater Vancouver Water District (GVWD), located in the lower mainland region of British Columbia, Canada, constructed a new water supply main in a tunnel under the Fraser River, just downstream of the Port Mann Bridge. This new water main will help ensure the continued, reliable delivery of clean, safe drinking water to municipalities south of the Fraser River. The steel water main was constructed within a 1 km (0.62 mile) long by 2.8 m (9.2 ft) inside diameter tunnel driven through soil, underneath the riverbed, connected by two 50 to 60 m (160 to 200 ft) deep shafts at the north and south ends of the tunnel. The shaft on the north side of the Fraser River was constructed with interlocking slurry wall panels to create a circular shaft approximately 8.16 m (27 ft) in diameter and 60 m deep. The final design required a 1.5 m (4.9 ft) thick circular reinforced cast-in-place (CIP) concrete wall to be placed within the slurry wall. The design of the shaft required a bond breaker acting as a slip liner between the slurry wall and CIP wall, so in the event of an earthquake, the circular reinforced CIP concrete wall can move freely relative to the slurry wall. An 8 m (26 ft) diameter shotcrete wall was to be applied to the slurry wall and a bond breaker installed against the finished shotcrete wall. Dry-mix shotcrete was selected to be applied to the slurry wall. Screed rails, which were to be installed every 1.5 m (5 ft), had a specified verticality tolerance of 10 mm (0.4 in.) between rails. The specified vertical tolerance of the final shotcrete wall was +5/–3 mm (+0.2/–0.1 in.) between screed rails.

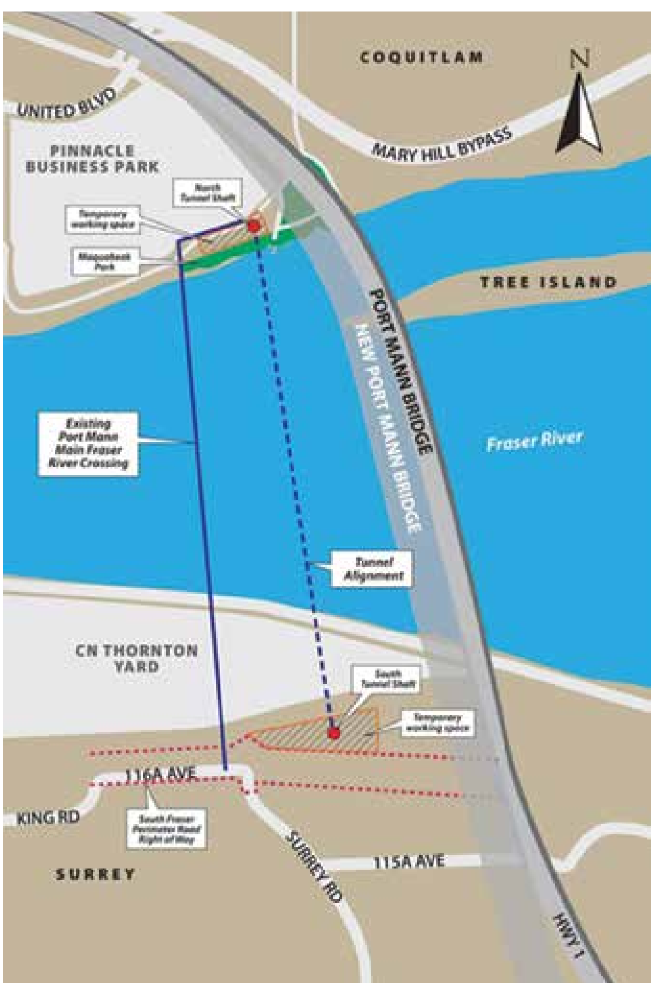

Fig. 1: Project overview and location

BACKGROUND

The Port Mann Main Water Supply Tunnel consists of a 1 km long tunnel under the Fraser River from Surrey to Coquitlam, BC, Canada (Fig. 1). The tunnel contributes to the water supply from the Coquitlam Reservoir and is part of the expansion and seismic upgrade of the GVWD water transmission system. The tunnel boring machine (TBM) used to bore the tunnel created a 3.5 m (11.5 ft) diameter cut that enabled the installation of the segmental lining that measured 3.3 m (10.8 ft) outside diameter and 2.8 m inside diameter.

Shafts were sunk at both the south and north ends of the tunnel. At the north shaft, the seismic design required the installation of a slip liner between the outer slurry wall

Fig. 2: Completed shotcrete wall with plastic slip liner installed

and the final reinforced CIP liner to eliminate the possibility of composite action between them in the event of seismic-induced deformations.

Shotcrete Lining Construction Method

A two-part system was developed that included shotcreting a smooth, circular wall against the slurry wall and then fastening a plastic liner to the wall. The CIP wall would then be placed against the plastic liner, which would act as the bond breaker required during a seismic event (Fig. 2).

The Contractor, working with the Engineer of Record, developed the following shotcrete construction method. A total of 12 steel columns were evenly spaced around the shaft collar (Fig. 3). A steel hollow structural section (HSS) was welded to the top of each column, as shown in Fig. 4. An FG-LL31 self-leveling Zenith Laser Plummet was screwed into the HSS with bolts, so that the laser line shot straight down with an accuracy of ±5 mm/100 m (±0.2 in./330 ft). The laser line was offset 50 mm (2 in.) from the theoretical perimeter of the 8 m diameter finished wall.

Screed rails were made from 13 mm (0.5 in.) round bar that was bent to match the radius of the shaft's final diameter. The screed rails were fixed in place by drilling and grouting several steel dowels circumferentially around the shaft wall every 1.5 m. For each screed rail, three lasers were used to position a curved aluminum template, which was clamped to the drilled dowels. The screed rails rested on the dowels and were clamped to the aluminum template (Fig. 5 and 6). Once in the correct position, the screed rails were welded to the dowels and the template was moved to the next screed rail position. Rails were installed to a tolerance of ±10 mm (0.4 in.), becoming the guide for shotcrete application.

Performing this work in a 60 m deep shaft required a mobile platform. The platform was used in two ways during construction. First, a crane-supported platform was used to install screed rails (Fig. 7). Once complete, the platform was transformed into a floating platform by attaching hollow

Fig. 3: North shaft slurry wall—Coquitlam, BC, Canada

Fig. 4: North shaft slurry wall with steel columns and laser setup

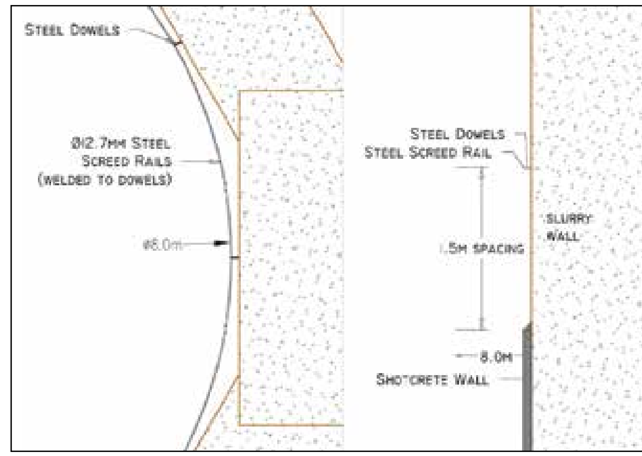

Fig. 5: Screed rail setup

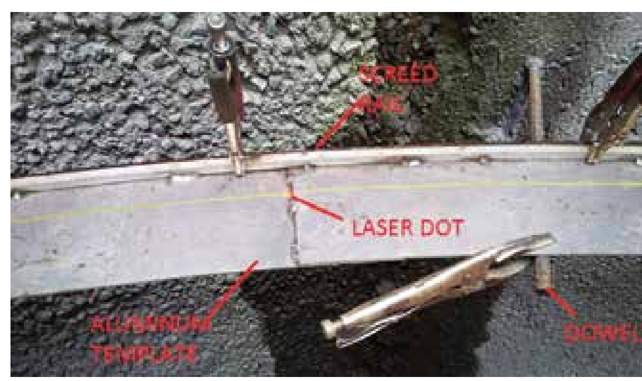

Fig. 6: Screed rail installation (looking down)

Fig. 7: Crane-lifted platform during rail installation

plastic floats below the deck (Fig. 8). Shotcrete was applied from this floating deck. The floating deck had many advantages during shotcrete application. It could carry the crew and equipment, and also catch the shotcrete overspray and rebound. There were no support cables in the way, and thus harnesses and lifelines were not required during shooting.

Once screed rails were installed throughout the shaft, the shaft was filled with water ready to accept the floating deck. Starting at the bottom of the shaft, the shotcrete liner procedure was as follows:

- Apply base course shotcrete to a height of 1.5 m, screed rail to screed rail. Approximately 25 mm (1 in.) of thickness was left for the finishing course.
- Shaft is filled with additional water until floating platform is raised to next lift.

Fig. 8: Floating platform during shotcrete application

- Shoot the next lift, add water, raise platform, and then repeat the process.
- Finishing from the bottom of the base course to the top of the shaft required approximately 36 lifts.
- Finishing course is applied to each lift from the top down by dewatering shaft until platform is lowered to next lift, apply finish course, and repeat.

SHOTCRETE MIXTURE DESIGN

The water table surrounding the north shaft was controlled by both tidal and river levels and was often near the ground surface. As a result, the slurry wall was under constant water pressure and there were leaks throughout the shaft causing water infiltration. A dry-mix shotcrete with maximum accelerator dosages was selected to help mitigate the water ingress.

The project specification required a 28-day compressive strength of 40 MPa (5800 psi). The main purpose of the shotcrete was to act as a filler to bring the slurry wall to a circular shape. Table 1 shows the concrete mixture designs used on the project.

Mixture B1 was applied for the base course shotcrete liner. Whenever water was observed coming out of the slurry wall, Mixture B2 was used to obtain faster set. Initially for dry areas, Mixture B3 was used to apply the finishing coat. During construction in October and November, the finish course shotcrete set more slowly because of cooler ambient temperatures and Mixtures B4, B5, and B6 were used as needed to reduce the setting time and speed up the finishing process. The accelerator dosage was designed

Table 1: Prebagged dry-mixed shotcrete mixture proportions per 1.0 m³

Material	Base course mixture (SSD) mass		Finish course (SSD) mass			
	B1, nonaccelerated (kg)	B2, accelerated (kg)	B3, nonaccelerated (kg)	B4, 1.5% accelerated (kg)	B5, 2.0% accelerated (kg)	B6, 3.0% accelerated (kg)
Cement (Type 10)	400	400	400	400	400	400
Fly ash (Type F)	0	0	0	0	0	0
Silica fume	40	40	20	20	20	20
Coarse aggregate, 12.5 mm (SSD)	420	420	0	0	0	0
Sand (SSD)	1320	1320	1760	1760	1760	1760
Estimated water (L)	180	180	180	180	180	180
Combined aggregate gradation	ACI 506R-16 Gradation No. 2[2]		ACI 506R-16 Gradation No. 1[2]			
Estimated as-shot air content (±1%)	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
Dry powdered accelerator, % by mass of cement	0	12	0	6	8	12
Totals:	2360	2372	2360	2366	2368	2372

*Note: 1 kg/m³ = 1.6856 lb/yd³

such that the finishers had enough time to screed and trowel the final shotcrete surface to the tolerance requirements. Heaters and hot water pressure washing were also used to increase the ambient and substrate temperature of the base course in the shaft.

PRECONSTRUCTION TRIAL SHOOTING AND NOZZLEMEN QUALIFICATION

Preconstruction trial shooting was essential for such an unusual dry-mix shotcrete project. The preconstruction trials were planned and conducted to:

a. Qualify the shotcrete mixture—testing to verify the shotcrete mixture met the project specification requirements (Fig. 9(a) and 9(b)).
b. Qualify the shotcrete nozzlemen for the project—the shotcrete nozzlemen used on the project were ACI-certified for dry-mix shotcrete in a vertical orientation. They shot qualification panels and mockup panels to demonstrate that they could place shotcrete meeting the project specification requirements.

A mockup test panel with the same curvature and thickness required for the project was set up at ground level on site for the preconstruction trial panels (Fig. 10(a) and 10(b)). Screed rails were installed to control the wall thickness. Each nozzleman was required to shoot one mockup panel and one material test panel for each mixture. Base course shotcrete Mixtures B1 and B2 were applied followed by application of the finish course shotcrete Mixture B3. The final surface finish was applied and tolerance was measured.

Cores were extracted from the mockup panels for visual evaluation of consolidation. Cores were extracted from the material test panels for determination of compressive strength test at 7 and 28 days, as well as boiled water absorption and volume of permeable voids at 7 days.

QUALITY CONTROL INSPECTION AND TESTING

Compressive strength of cores extracted from material test panels served as the primary quality control testing. However, some compressive tests for the base course shotcrete were lower than expected. Therefore, in-place cores were taken and tested for the base course shotcrete with 3% accelerator. Cores for the finish course shotcrete were all extracted from test panels.

Fig. 9: Nozzlemen qualification: (a) shooting test panels; and (b) setting time and early strength tested for each mixture

Fig. 10: Preconstruction mockup panel: (a) shooting mockup panel; and (b) closer view of mockup panel

Figure 11 shows the compressive strengths for all the cores extracted from test panels for the finish course dry-mix shotcrete were over 25 MPa (3600 psi) at 7 days, and nearly all were higher than 40 MPa at 28 days except for one test with 38 MPa (5500 psi) shot on December 6, 2013. This shows that with a single exception, the shotcrete met the specified compressive strength of 40 MPa at 28 days.

Figure 12 shows the compressive strength of cores extracted from test panels and in-place base course shotcrete (the dry-mix shotcrete with 3% accelerator). A set of three cores was extracted from test panels for every day of shotcrete application. Some cores did not reach the required compressive strength of 40 MPa at 28 days. Prior to applying the finish course, in-place cores were taken of suspect lifts. All lifts exceeded 35 MPa (5100 psi) compressive strength and almost all lifts exceeded 40 MPa compressive strength, which was considered acceptable by the Engineer.

DRY-MIX SHOTCRETE SETUP

The dry-mix shotcrete process facilitated easy access, allowed frequent movement of equipment, and helped with dust control. The dry-mix shotcrete process results in higher rebound compared to the wet-mix shotcrete process. When using dry prebagged materials, dry-mix shotcrete application requires the use of a predampener with a hopper that can load 1 yd^3 (0.8 m^3) of prebagged materials into a rotary gun. A delivery hose, air compressor providing air flow at 24 m^3/min (850 ft^3/min) at a pressure of 0.83 MPa (120 psi), and dry-mix nozzle connected to a water supply hose were used. The predampener is essential for the dry-mix shotcrete process when using prebagged materials. It dampens the dry-mix concrete materials to a moisture condition of about 4 to 6% (Fig. 13(a) and 13(b)), reducing dust, facilitating transport of the material through the hose, and reducing the risk of shock from static electricity.

The dry-mix machine and predampener were set up at the surface, and hoses 35 to 60 m (100 to 200 ft) long were used to convey the materials to the nozzleman on the floating deck.

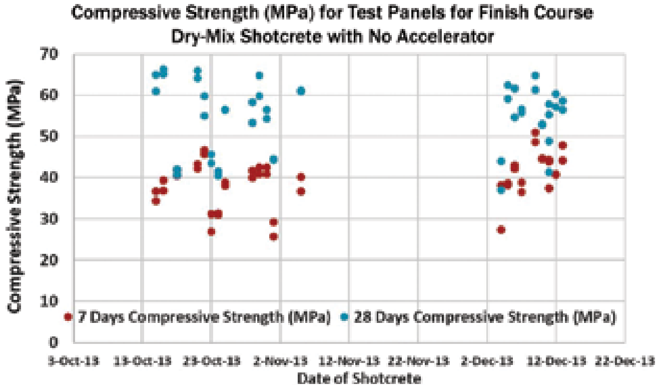

Fig. 11: Compressive strength for cores extracted from test panels for finish course dry-mix shotcrete without accelerator (Note: 1 MPa = 145 psi)

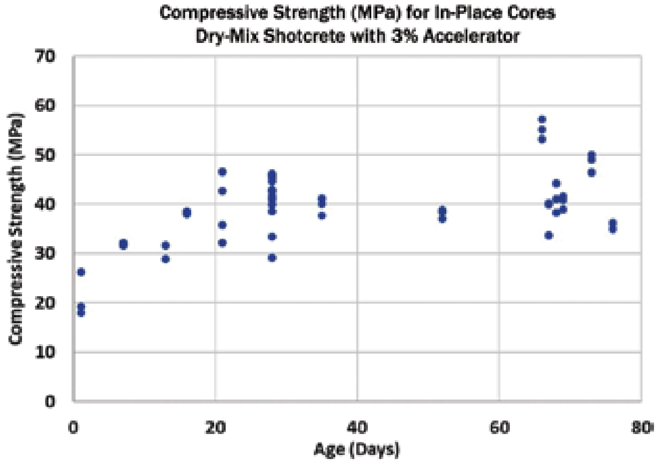

Fig. 12: Compressive strength from in-place cores, base course shotcrete (Note: 1 MPa = 145 psi)

Fig. 13(a) and (b): Dry-mix shotcrete machine with predampener

Fig. 14: Finished base course shotcrete

Figure 14 shows the base course shotcrete of up to 180 mm (7 in.) thick, with ACI 506R-16 (Table 1.1.1) Gradation No. 2 shotcrete (containing coarse aggregate) with 3% accelerator used to fill the gap between the slurry wall and steel screed rails and creating a smooth circular surface. Approximately 25 mm was left for final finish shotcrete application.

The following procedure was used for the finishing course:

1. Blow off excessive water on the surface of the base course layer of shotcrete;
2. Apply shotcrete (Fig. 15 and 16); and
3. Finish shotcrete.

Construction sequence and timing are critical. The substrate surface moisture condition was kept SSD (saturated surface-dry) during Step 1. The finishing took place right after Step 2. It was critical to finish the final shotcrete surface before the dry-mix shotcrete (with accelerator) reached initial set. This was usually about 5 to 10 minutes after shotcrete application.

CONSTRUCTION CHALLENGES

Cold Weather Shotcrete

As the project progressed into November and December, the ambient temperature on site dropped to 5°C (40°F) or

Fig. 15: Application of finish coat dry-mix shotcrete from floating deck

Fig. 16: Birds-eye view of dry-mix shotcrete application from the floating deck. Note the low dust and simple setup of the shotcrete operation. Horizontal screed rails to control the base course thickness were spaced at 1.5 m

lower. This delayed setting of the shotcrete and affected finishing practices for the shotcrete finish course. Several heaters were installed in the shaft, and the base course surface was cleaned with high-pressure hot water and steam, with temperatures of 90 to 100°C (194 to 212°F). The shotcrete material temperature was kept at 12°C (54°F) or higher to allow the cement to hydrate with proper setting and early-age strength development. Additionally, the shaft was covered and heated overnight. Dry-mix material bags were also kept above 20°C (68°F) using tarps and heaters.

Finishing

The base course shotcrete was left with an as-shot finish. The finish course was given a steel trowel finish (Fig. 17(a) and 17(b)). A total of a three mixture designs were applied to the walls. In areas with little to no groundwater present, Mixture B3 with no accelerator was used. In areas with light to moderate flows of groundwater, Mixture B4 with 1.5% accelerator was used. In areas with heavy groundwater flows, Mixture B6 with 3% accelerator was used. In the areas using the B3 or B4 mixtures, it was often required to install drainage pipes to allow a path for water to escape during application and setting. Mixture B6 took approximately 5 to 10 minutes to set in cooler weather, allowing the finishers ample time to finish the surface, while setting fast enough to stop water inflows. The drainage pipes were later removed and the remaining holes were dry packed with grout.

Water Leakage from the Slurry Wall

This shaft is alongside the bank of the Fraser River and is subject to high groundwater levels. Water ingress is quite common in a slurry wall shaft through the cold joints between overlapping panels. The high hydrostatic pressure from the leakage made it nearly impossible to stop water inflows. Sodium silicate grout was injected behind the shaft slurry wall to help reduce water leakage through the slurry wall. Additionally, the base course substrate was dried using an air lance (blow pipe) and the dry-mix shotcrete nozzle used with water and air only (no concrete materials) to bring the surface to an SSD condition immediately prior to shooting the finish course. This was found to be effective for base course shotcrete application and final finishing most of the time. However, there were some occasions where a buildup of water pressure on the base course shotcrete behind the finish course caused bulges in the finish course shotcrete, as shown in Fig. 18(a) and 18(b). These areas were cut out

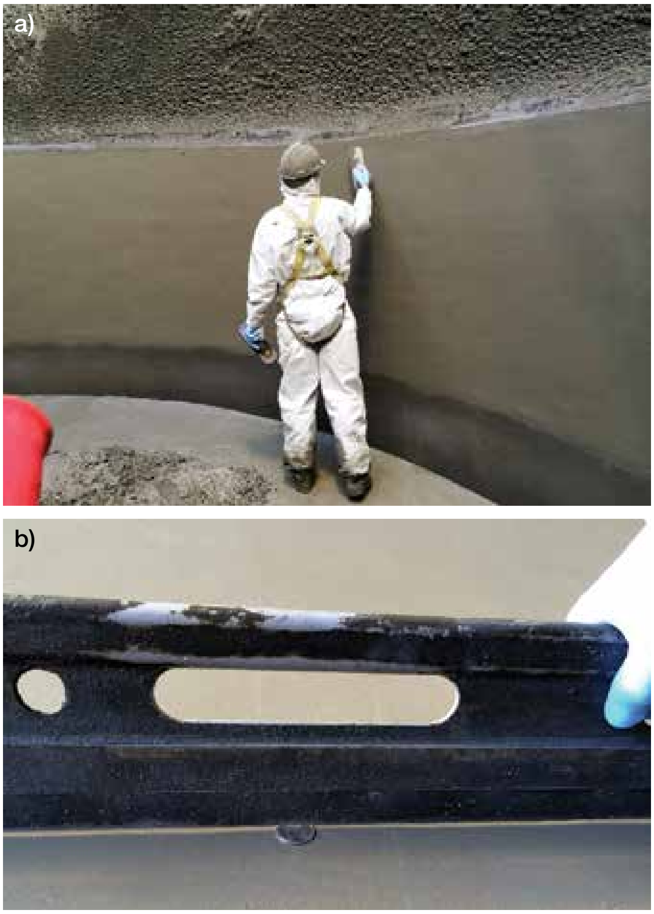

Fig. 17: (a) Steel trowel finishing; and (b) checked finish tolerance with a Canadian quarter, which is less than 2 mm thick

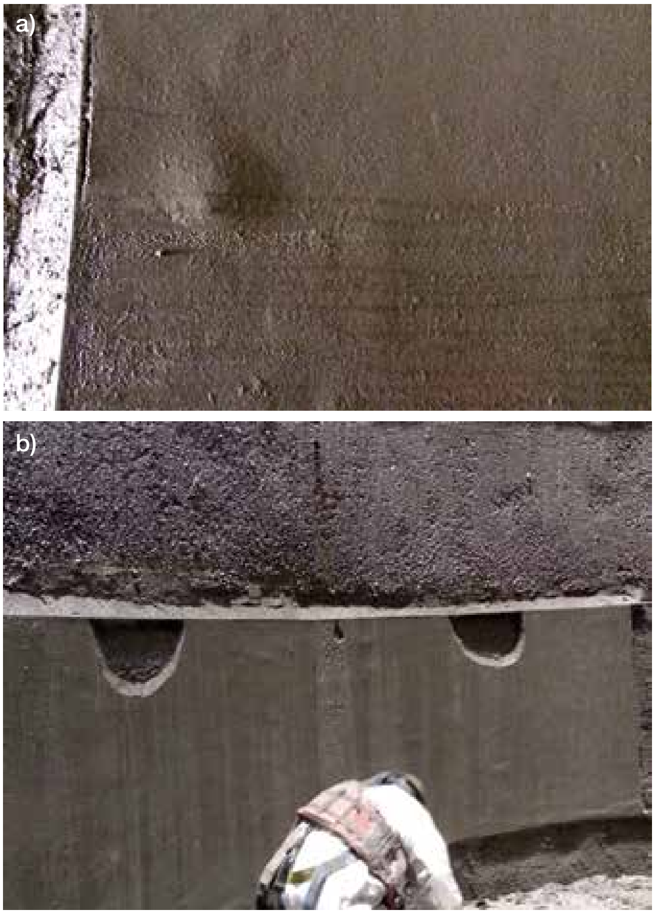

Fig. 18: (a) Water pressure buildup at the back of the finish course shotcrete; and (b) the shotcrete popouts were cut off and repaired with shotcrete when the shaft was dry

and repaired with highly accelerated shotcrete and a drainage pipe.

Summary of Dry-Mix Shotcrete Work

- Hanging/floating deck: The suspended, then floating deck was a very innovative way to move between lifts during screed rail installation and the shotcrete application. It was cost effective and reduced the construction schedule. In addition, water in the shaft for floating the deck provided water curing for the shotcrete lining. All these proved a distinct benefit compared to other decking options, such as scaffolding the entire shaft.
- Dry-mix shotcrete application: Dry-mix shotcrete was selected due to its inherent application flexibility, fast setting time, and ability to deal with groundwater leakage into the shaft. The predampened dry-mix shotcrete was placed with good control of rebound and overspray. It should be noted that overspray or waste was far less than expected, resulting in approximately 10 to 20% of the total volume. The dry-mix shotcrete prebagged material worked well in providing final liner construction with varying thickness. Rigorous quality control inspection and testing confirmed the high quality of the shotcrete placement.
- Cold weather shotcrete: During cold weather, when ambient temperatures fell below 5°C, additional precautions and protective measures were implemented. Pressure washing with hot water properly prepared the base course shotcrete substrate, raising the surface to the temperature needed for receiving the final finish course shotcrete appropriate for the specific accelerator dosages used. Keeping the area warm with heaters, as well as keeping dry mixed bags warm prior to placement, was also effective. The finish course shotcrete was designed to set up quickly, while still allowing sufficient time for steel trowel finishing to the specified tolerances.

Conclusions

- Dry-mix shotcrete, when properly applied, can provide a high-quality shotcrete lining, especially for liners with irregular shapes requiring varying thickness.
- The floating deck construction method is an innovative construction method for shaft lining construction. It

improved the quality of shotcrete construction; reduced rebound and overspray; reduced the construction schedule, labor, and materials costs; and thus reduced the overall cost of the project.

- Special measures need to be adopted to deal with the buildup of water pressure behind a layer of freshly applied shotcrete. The procedures described in this report were effective in dealing with this problem.

References

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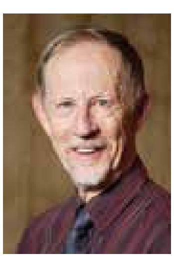
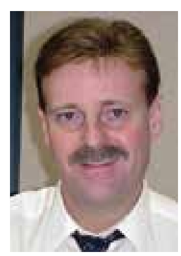


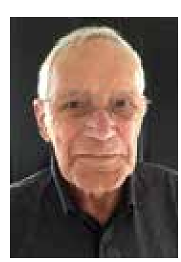
D.R. (Rusty) Morgan*, FACI, is a Civil Engineer with over 50 years of experience in the concrete and shotcrete industries. He served as a member and Secretary of ACI Committee 506, Shotcreting, for over 25 years. He is a past member of ACI Committees 365, Service Life Prediction, and 544, Fiber-Reinforced Concrete. Morgan is a founding member and Past President of ASA. He is an ASA/ACI C660-approved Shotcrete Nozzleman. Morgan is a past member of the Canadian Standards Association Concrete Steering Committee and was a Canadian Representative on the International Tunnelling and Underground Space Association Committee, Shotcrete Use. He has worked on over 1000 concrete and shotcrete projects around the world during his consulting career and has edited five books and published over 150 papers on various aspects of concrete and shotcrete technology. In 2001, Morgan was elected as a Fellow of the Canadian Academy of Engineering.*

Brian McInnes *is a Project Engineer for McNally Construction Inc. with over 8 years of experience in both tunneling and marine industries. He has held several roles such as Civil Coordinator, Project Engineer, and Project Manager on various projects, including the Dixie Road Tunnel, Port Mann Main Water Supply Tunnel, and the Five Finger Marine Outfall. McInnes was responsible for developing the construction execution plan for the shotcrete work on Port Mann as well as managing the execution of the work.*



Allen Mitchell *is a Senior Project Engineer at Metro Vancouver and was the owner's Project Manager for the Port Mann Water Supply Tunnel project.*

Andrew Rule *has more than 25 years of experience in the construction industry across North America. He has held positions from General Laborer and Equipment Operator through Project Manager. Rule specializes in technically challenging, engineering-intensive projects in the heavy civil and tunnel sectors.*



Ted Walter *is President and Owner of Can-Tech Shotcrete Inc. of Burnaby, BC, Canada. Since incorporation in 1988, Can-Tech Shotcrete Inc. has specialized in the application of wet-mix and dry-mix shotcrete in tunnels, in the repair of marine structures, and seismic upgrade of buildings and dams. Over the past 30 years, Walter has completed many unique and challenging shotcrete projects, such as the North Shaft shotcrete liner.*