2022 Outstanding Infrastructure Project

Shotcrete at Mount Pleasant Station on the Eglinton Crosstown LRT Project in Toronto, Canada

By Shaun Radomski, Lloyd Keller, Daniel Sanchez, and Dudley R. (Rusty) Morgan

Fig. 1: Finished Shotcrete wall at Mount Pleasant Station

Multi-million dollar underground stations are currently under construction on Metro and LRT lines in Toronto, Ontario, Canada. Traditionally, the thick, heavily reinforced structural concrete station walls have been constructed using the conventional form-and-pour concrete construction method. This construction method, while widely used, is not without its challenges. Many of the underground station sites are in congested urban areas with limited spaces for laydown of concrete formwork, and crane access time for handling and installation of formwork is often on a critical path for completion of station construction. In addition, in conventional ground-up forming, scheduling and logistics has necessitated that construction in a top-down method be employed. This method of construction, and the requirement for a series of transverse large wall supporting struts, makes setting and moving the formwork wall panels cumbersome and impractical using traditional crane hoisting methods. Recognizing these difficulties, the Joint Venture Design and Build companies constructing these underground stations have asked the following question: "Can wet-mix structural shotcrete be used in lieu of conventional form-and-pour concrete to construct these thick, often 1.0 m (39 in.) to 1.5 m (4.9 ft), heavily-reinforced mass concrete walls with embedments (electrical conduits, steel plates, grouting tubes, and PVC water stops at vertical and horizontal construction joints) and thus largely eliminate the need for the use of formwork?"

Initially, there was skepticism in the industry in Ontario as to whether this was feasible. Reasons cited for not using shotcrete included the following:

- The heat of hydration in high-paste content concrete for the thick walls could cause thermal cracking
- There was no experience using 70% slag mixes to control heat of hydration in thick concrete sections
- Concern for increased drying shrinkage cracking due to shotcrete's higher paste content
- Proper consolidation with shotcrete placement in thick, heavily congested walls with large diameter, closely spaced reinforcing steel
- Lack of experienced, qualified structural shotcrete inspectors in Ontario

However, engineers with decades of experience in

Fig. 4: Compressed air blow pipe working in tandem with nozzleman during bench shooting.

Fig. 2: Shotcrete wall construction at tunnel openings

Fig. 3: Green Line G783-200 Fabric Concrete Placement Hose with an inner diameter of 50 mm (2 in.) connected to a nozzle assembly utilizing a unique pipe extension between the rubber nozzle tip and the nozzle air ring. Rubber nozzle tip is wrapped tight with grey duct tape.

Fig. 5: A long 40 mm (1.5 in.) diameter stiff rod vibrator provided the placed shotcrete with supplementary consolidation. Credit: Jimmy Wang.

shotcrete confirmed wet-mix shotcrete was a viable construction method. Using shotcrete placement provided a high-quality end product for the owners with valuable time and cost savings for the projects.

Based on successfully addressing all the concerns in a detailed study, the joint venture consortium, Crosslinx Transit Solutions (CTS), and the designers and constructors of the Mount Pleasant Station on the Eglinton Crosstown Light Rapid Transit Line in Toronto, elected to proceed using a low carbon, low heat of hydration 70% slag concrete mixture for construction of the structural mass shotcrete perimeter walls at this station.

CTS designers required the concrete mix to meet the following design performance requirements:

- Compressive strength of 35 MPa (5000 psi) within 56 days
- Maximum water to cementitious materials ratio of 0.40
- Rapid chloride ion penetration of 1500 coulombs within 91 days

- "As-batched" plastic air content of 7-10% at discharge into the pump and "As-shot" plastic air content of 5+/- 1.5% after shooting in-place
- Slump of 90 mm +/- 20 mm (3.5 in. ± 0.8 in.) at discharge into the pump
- Maximum heat of hydration in the center of the mass shotcrete walls to not exceed 70°C (158 °F), and the temperature differential between the near surface and the center of the mass shotcrete walls not to exceed 20°C (68 °F)

The concrete mixture was designed with 30% GUbSF Portland cement and 70% slag cement. A natural cellulose fibre at 0.45 kg/m³ (1.14 lb/yd³) dosage was incorporated into the mix to enhance pumpability, shootability, adhesion/cohesion, stackability, and finishability. It also helped mitigate plastic and drying shrinkage cracking.

Shotcrete equipment was typical for wet-mix shotcrete. The nozzle assemblies were modified to address the thicker walls. The custom nozzle assembly used the following:

- A unique pipe extension to reduce the shooting distance to the receiving surface at the back of the wall (Fig. 3)
- A rubber nozzle tip wrapped with duct tape to reduce bulging of the nozzle tip during bench shooting, which provided a more concentrated shotcrete stream and a "rifling" type action
- In thick sections, supplemental consolidation around the back-reinforcing steel bars to the outer wall face was provided by a stiff-rod vibrator (Fig. 5) with a 40 mm (1.5 in.) diameter.

Each ACI-certified wet-mix nozzleman underwent prequalification by shooting a section of a full scale 1.3 m (4.3 ft) thick heavily reinforced mockup representing a perimeter station wall at Mount Pleasant Station (Fig. 7). After shooting the mockup, several block sections were cut open with a wire saw, and upon close evaluation, the quality of shotcrete around the reinforcing steel and to the outer membrane was observed to be excellent. (Fig. 8 and Fig. 9)

Construction began (Fig. 10) following the first wave of COVID-19, continued during the Delta variant wave, and ended at the onset of the Omicron variant wave. Not to

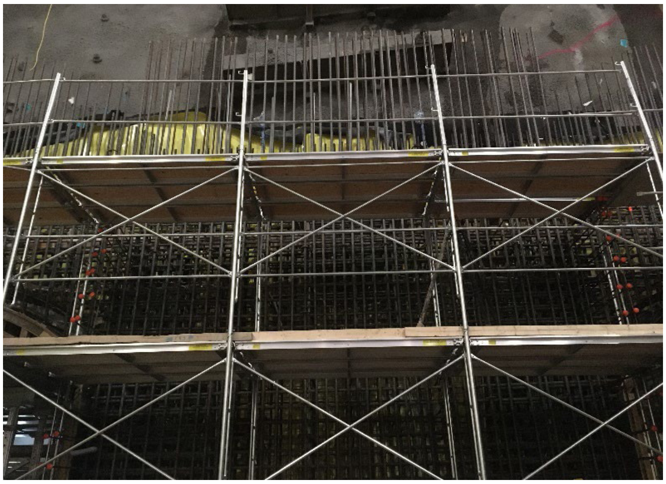


Fig. 6: Multi-level scaffolds were used to provide nozzleman with clear and safe access to the work

Fig. 7: Full-scale 1.3 m thick station wall mock-up

Fig. 8: A wire saw cut section of mockup showing excellent consolidation of shotcrete around the three layers of #35M (#11) rebar at the back of the work and to the outer membrane next to the embedded plastic water stop. Credit: Jimmy Wang.

Fig. 9: Another example of a wire saw cut section of mockup showing excellent quality of shotcrete at the transition between the shotcrete and the self-consolidating poured concrete

Fig. 10: A close-up view of the shotcrete contactor's nozzleman bench shooting (background) followed by an operator of a long stiff rod vibrator (foreground) being inserted into the work to "lay down the bench" and provide the shotcrete with supplementary consolidation around the back reinforcing steel.

overstate the issue, but this posed many challenges to CTS to stay on schedule while keeping all personnel safe. Very strict safety protocols were implemented onsite by CTS.

A total of 7200 m^3 (9400 yd^3) of concrete was supplied to the project and routinely met the plastic shotcrete properties of 90 mm +/- 20 mm slump at discharge into the pump and 7- 10% plastic air content at discharge into the pump. Compressive strength satisfied the specified minimum compressive strength of 35 MPa (5000 psi) at 56 days. Thermal monitoring data revealed the temperature rise in the center of the mass shotcrete walls satisfied the 70°C (158 °F) limit and the temperature differential between the near surface and the center of the mass shotcrete walls satisfied the 20°C (68 °F) limit.

Final coat was shot, cut and finished to the specified line and grade of shooting wires. The specified final finish was provided using floats and trowels. The finished surfaces were free of voids, sags, tears, or plastic shrinkage cracks. All shotcrete rebound, overspray, and cuttings were removed from the work and disposed of in an environmentally acceptable way. All shotcrete was cured to minimize drying shrinkage cracking for at least 7 days from time of shotcrete placement.

This project has elevated the knowledge and acceptance in the Toronto construction community on the use of shotcrete to construct thick (up to 1.5 m), heavily reinforced metro or LRT underground station structural walls using the "hybrid" (shoot and vibrate) shotcrete construction method, with high-volume slag concrete mixtures (up to 70% slag). Success required careful planning, control of the concrete mixture design, appropriate preconstruction mockups, qualified ACI-certified nozzlemen, attention to consolidation throughout the thick wall sections, testing, and qualified inspectors.

2022 OUTSTANDING INFRASTRUCTURE PROJECT

Project Name
Eglinton Crosstown LRT Project at Mt Pleasant Station | Toronto, Canada

Shotcrete Contractor
Torrent Shotcrete Structures Ltd.

Architect/Engineer
SNC-Lavalin

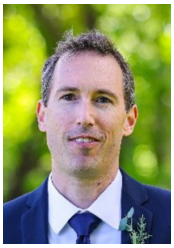
Material Supplier/Manufacturer
Innocon Ready Mix & Canada Building Materials

Equipment Manufacturer
REED Concrete Pumps

General Contractor
Crosslinx Transit Solutions

Shotcrete Consultants and Quality Inspections
WSP E&I Canada Ltd.

Project Owner
Metrolinx & Infrastructures Ontario



Shaun M. Radomski *is a Civil Materials Engineer specializing in concrete and shotcrete technology and the evaluation and rehabilitation of infrastructure. He has over 17 years of civil materials engineering, inspection, and testing experience in Canada and the United States. He is a member of ACI Committees 506, Shotcreting; and 661 Shotcrete Inspector Certification. Based in Calgary, AB, Canada, Mr. Radomski has extensive shotcrete consulting, inspection, and testing experience across North America, all with WSP and its predecessor companies. He has experience with both wet-mix and dry-mix shotcrete, vertical and overhead shotcrete, mass shotcrete, shotcrete underground, alkali-free-accelerator addition at the nozzle, and incorporating steel fiber, polypropylene fiber, natural hemp, and cellulose-based fibers in shotcrete mixes for added toughness, enhancing adhesion/cohesion, finishability, curing, and for controlling shrinkage cracking. Radomski received a Master's Degree in Civil Engineering from Ryerson University, Toronto, ON, Canada, where he conducted research on using SCM's to enhance the durability of concrete against sulphate attack and alkali aggregate reactivity.*

Lloyd Keller *is the founder of Research and Development and Quality Control for EllisDon Construction in Mississauga, ON, Canada. He is a Fellow with ACI and participates in numerous committees for ACI and CSA in Canada. He was educated at BCIT in Canada specializing in Civil and Structural Engineering Technology. His research efforts over the last number of years have focused on Self Consolidation Concrete (ACI 237) and the prediction of formwork pressure. Other areas of his research over the last few years have been the use of shotcrete for structural installations and the control of exothermic heat generation with the utilization of high-volume supplementary cementing materials.*

Daniel Sanchez *is a Professional Engineer with over two decades of experience in the heavy civil infrastructure construction industry. Highly experienced in the lifecycle of the project from conceptual design through development and delivery, he has participated in numerous underground projects in Spain and Canada, including Metro Line 9 in Barcelona, the Eglinton Crosstown LRT in Toronto, and the Scarborough Subway Extension. Daniel holds a Master's Degree in civil engineering from the University of Granada, Spain.*

Dudley 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 Examiner. Morgan is a past member of the Canadian Standards Association Concrete Steering Committee and was a Canadian Representative on the International Tunneling and Underground Space Association Committee, Shotcrete Use. He has worked on over 1200 concrete and shotcrete projects around the world during his consulting career, he has edited seven books, and he has published over 165 papers on various aspects of concrete and shotcrete technology. In 2001, Morgan was elected as a Fellow of the Canadian Academy of Engineering.*

Editor's note: *Watch future issues of Shotcrete magazine for a two-part series of articles with more detailed insight into the pre-construction and construction phases of this project.*