Mount Pleasant Station, Part 1: Preconstruction Qualification for Shotcreting of Mass Concrete

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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 areas for laydown of concrete formwork, and with crane access time for handling and installation of formwork often on the critical path for completion of station construction. In addition, in conventional ground-up forming, scheduling and logistics have 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 question: "Can wet-mix structural shotcrete placement be used in lieu of conventional form-and-pour concrete to construct these, often 1.0 m (3.3 ft) to 1.5 m (4.9 ft) thick heavily reinforced mass concrete walls with a variety of embedments (electrical conduits, steel plates, grouting tubes, and PVC waterstops at vertical and horizontal construction joints) and thus largely eliminate the need for the use of vertical formwork?"

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

a) The walls were too thick; given that wet-mix shotcrete typically has a high cement or paste content (around 450 kg/m^3 [750 lb/yd^3]), the heat of hydration, and peak and differential shotcrete temperatures would be too great and could result in thermally induced cracking and damage in the station walls. The design of the system had taken into consideration the necessity to reduce the potential for both thermal and drying shrinkage cracking. High cement content and smaller coarse aggregate sizes in traditional shotcrete mixtures conflicts with the need to reduce and minimize shrinkage.
b) While the issue of the heat of hydration in mass form-and-pour concrete walls had been dealt with in Ontario by using 70% slag replacement of portland cement in concrete mixtures (Ref. 3), there was no precedence for the use in structural shotcrete. There was uncertainty as to whether such high percentage of slag shotcrete mixtures could be satisfactorily pumped, shot, stacked, and finished without sagging and sloughing.
c) The thickness of walls and heavy congestion of large diameter, closely spaced reinforcing steel bars (up to four and sometimes more layers of lapped 30M or 35M bars [#9 or #11]), as well as embedments, would make it impossible to get full consolidation of shotcrete around such bars and embedments.
d) There was a lack of certified and qualified shotcrete nozzlemen in Ontario with demonstrated, proven experience in the construction of such heavily reinforced structural shotcrete walls.
e) There was a lack of experienced, qualified structural shotcrete inspectors in Ontario to monitor and sign off on the acceptability of the constructed shotcrete work.

Based on decades of experience in the concrete and structural shotcrete fields, the authors in Reference 1 and Reference 2 believed that the concerns above could all be satisfactorily addressed, and that the use of wet-mix shotcrete for construction of the structural walls in these underground stations was a viable construction method, which could provide a high-quality end product for the Owners with valuable time and cost savings for the projects.

The concerns in Item a) above were addressed in a systematic study undertaken to develop a low heat of hydration mass shotcrete which would meet the CSA A23.1

requirements such that the peak temperature of the in-place shotcrete would not exceed 70°C (160°F) and with an appropriate thermal control plan that the temperature differential between the core and exposed shotcrete surface would not exceed 20°C (70°F). This was accomplished using a 70% slag shotcrete mix. A detailed thermal control plan comparing the potential strain developed versus the strain capacity of the candidate concrete mixtures (generally in compliance with methods described in CIRIA C 660 and CSA A23.1 Annex T) confirmed the compliance with the empirical temperature constraints described previously. Details of this study are provided in Reference 1. The issue of concerns regarding possible restrained shrinkage cracks were addressed by using the 70% slag mix which provides low shrinkage where both test panels and full-scale mock-ups were found to be crack-free, as detailed in Reference 2.

The concerns outlined in Item b) above were alleviated. It was demonstrated in the study detailed in Reference 1 and Reference 2 that the selected 70% slag shotcrete mix was able to be satisfactorily pumped, shot, stacked, and finished without any significant problems of excessive plugging in the delivery line or sagging and sloughing of the shotcreted material in-place.

The concerns listed in Item c) above regarding the constructability of these thick, heavily reinforced structural shotcrete walls were dealt with by adoption of a "hybrid" (shoot and vibrate) shotcrete construction method. Details of the method used are provided in Reference 2. It was shown in the construction of full-scale mockups, from which "windows" were cut out of the thick structural walls with a diamond wire saw, that both full encapsulation of reinforcing steel, as well as embedments and walls free of voids and defects could be achieved. Six shotcrete nozzlemen were qualified to shoot structural shotcrete walls for an underground station, thus addressing the concern listed in Item d) above.

Finally, with respect to Item e) above, regarding the need for qualified structural shotcrete inspectors to monitor and sign off on the acceptability of the constructed work, a comprehensive shotcrete inspector education and training program was developed and provided by the authors. It also included a detailed Shotcrete Inspection Checklist which is now being routinely used by qualified Shotcrete Inspectors on Metro station construction projects in Toronto.

Based on successfully addressing all the issues raised in the list of concerns above, 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 with using this low carbon, low heat of hydration 70% slag shotcrete for construction of the structural mass shotcrete perimeter walls at this station. This paper provides details of the Mount Pleasant Station pre-construction mock-up phase of this work. More specifically, it provides details of:

- Structural wall design details for the mock-up
- Shotcrete performance requirements and shotcrete mixture design submittals
- Qualification of shotcrete mixture design and ten shotcrete nozzlemen in shooting full-scale station wall mockups
- Qualification of shotcrete inspectors

STRUCTURAL WALL DESIGN DETAILS FOR THE MOUNT PLEASANT STATION PRE-CONSTRUCTION MOCK-UP

Figures 1 and 2 show the reinforcing design details for the 1.3 m thick perimeter station wall shotcrete mock-up used to pre-qualify both the mixture design and the shotcrete nozzlemen for the Mount Pleasant Station.

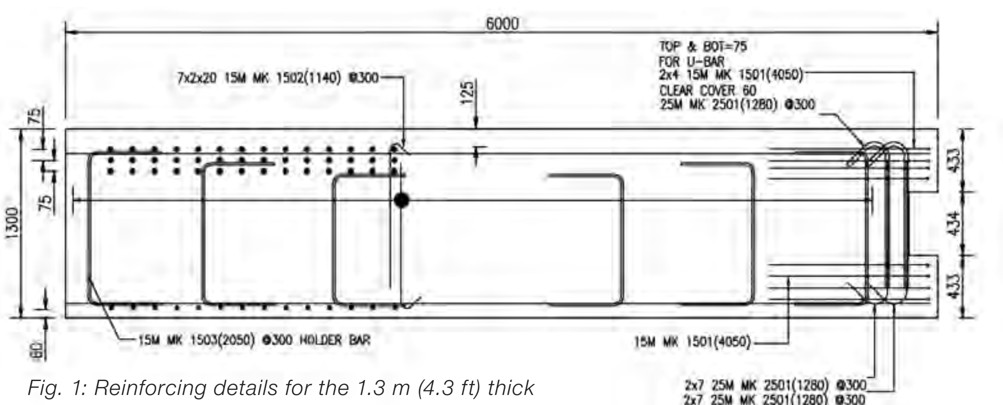

Fig. 1: Reinforcing details for the 1.3 m (4.3 ft) thick perimeter station wall shotcrete mock-up – Plan View.

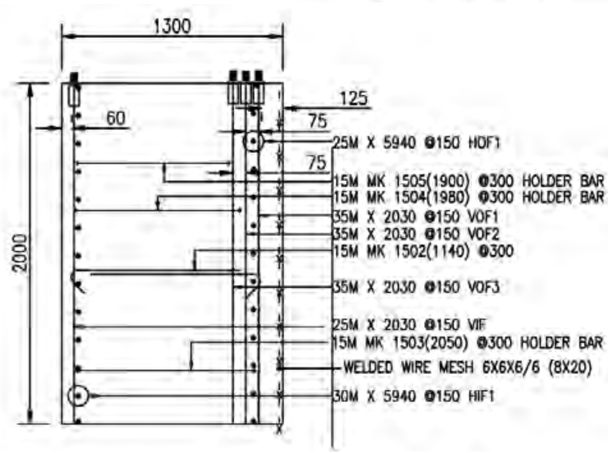

Fig. 2: Reinforcing details for the 1.3 m thick perimeter station wall shotcrete mock-up – Section View.

SHOTCRETE PERFORMANCE REQUIREMENTS AND SHOTCRETE MIXTURE DESIGN SUBMITTALS

CTS designers required the shotcrete mixture design to meet the following performance requirements:

- Compressive strength of 35 MPa (5000 psi) within 56 days
- Maximum water to cementing materials ratio of 0.40

- Rapid chloride ion penetration (CSA A2.3.-23C) of 1500 coulombs within 91 days
- "As-batched" plastic air content of 7-10% at discharge into the shotcrete pump
- "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 shotcrete pump
- Maximum heat of hydration in the centre of the mass shotcrete walls to not exceed 70°C (158°F)
- The temperature differential between the near surface and the centre of the mass shotcrete walls not to exceed 20°C (68°F)

Two ready-mix concrete producers underwent pre-construction mixture design qualification to supply a wet-mix shotcrete for this work. Each mixture was designed with 30% GUbSF portland cement and with 70% slag cement. A natural cellulose fibre at 1.5 lbs/m^3 (0.7 kg/m^3) dosage was incorporated into the mixture to enhance pumpability, shootability, adhesion, cohesion, stackability, and finishability of the mixture. The fibre also helped mitigate plastic, autogenous, and drying shrinkage cracking.

SHOTCRETE EQUIPMENT USED IN THE PRE-CONSTRUCTION MOCK-UP

Shotcrete equipment included a 46 m^3/hr (60 yd^3/hr). TK60HP pump and two 10.6 m^3/min (375 ft^3/min) 375H air compressors (Fig. 3). Shotcrete was pumped from the hopper into a 90° steel elbow with an initial inside diameter of 127 mm (5 in.). Following the 90° steel elbow, the inside diameter of the steel line was reduced to 100 mm (4 in.), and then gradually reduced to 75 mm (3 in.) before a 45-degree elbow clamped to a short 75 mm slick line with 10 MPa (1450 psi) pressure rating. At another reducer, a 50 mm (2 in.) slick line traveled 3 m (10 ft) before the steel line was transitioned to 15 m (50 ft) of New-Line G783-200 Fabric Concrete Placement hose with 8.5 MPa (1230 psi) pressure rating feeding shotcrete to the mock-up. All connections in the shotcrete delivery system used clamp gaskets, rubber seals, pins, and whip checks. Shotcrete was pumped a total length of approximately 30 m (100 ft) to the mock-up (Fig. 4).

The nozzle assembly (Fig. 5) utilized the following:

- A unique pipe extension to reduce the shooting distance to the receiving surface at the back of the wall
- A rubber nozzle tip wrapped with duct tape to reduce bulging of the nozzle tip during bench shooting, which provided the shotcrete with a more concentrated shotcrete stream and a "rifling" type action

Compressed air was fed to the nozzle assembly using 30 mm (1.2 in.) air delivery hoses with 2.8 MPa (400 psi) pressure rating. A separate air compressor fed compressed air to two blow pipes. The reason for the separate compressor was to avoid stealing any air from the nozzle during bench shooting and blow piping simultaneously. A long, stiff rod vibrator with a 40 mm (1.6 in.) diameter (Fig. 6) provided the shotcreted concrete with supplementary consolidation.

Fig. 3: 375CFM Air Compressor and Putzmeister TK60HP Shotcrete Pump.

Fig. 4: Steel slickline and rubber hose which fed shotcrete to the mock-up. Credit: Jimmy Wang.

Fig. 5: Nozzle assembly utilizing a unique pipe extension between the rubber nozzle tip and the nozzle air ring compressed air valve. Rubber nozzle tip is wrapped tight with grey duct tape. Credit Jimmy Wang.

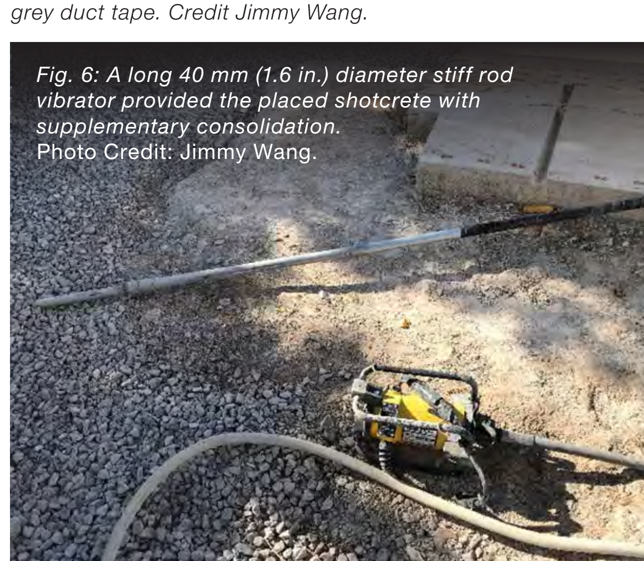

Fig. 6: A long 40 mm (1.6 in.) diameter stiff rod vibrator provided the placed shotcrete with supplementary consolidation.
Photo Credit: Jimmy Wang.

QUALIFICATION OF SHOTCRETE MIXTURE DESIGN AND SHOTCRETE NOZZLEMAN BY SHOOTING FULL-SCALE STATION WALL MOCKUPS

ACI-certified shotcrete nozzlemen underwent prequalification by each shooting a section of a full scale 1.3 m (4.3 ft) thick heavily reinforced mock-up representing a perimeter station wall at Mount Pleasant Station (Fig. 7, 8, and 9). The mock-up consisted of three layers of closely spaced 35M reinforcing bars at the back of the work adjacent to a waterproofing membrane system; it also contained grout tube embedments and one layer of closely spaced 35M rebar along the front inner wall face of the mock-up. Each nozzleman was responsible to shoot a separate rectangular 2 m (6.6 ft) long, 1.0 m (3.2 ft) high, and 1.3 m thick block segment of the mock-up, as shown in Figures 7, 8, and 9.

During the mock-up construction, the mixture design underwent prequalification and was evaluated for its pumpability, shootability, stackability (adhesion and cohesion using "beehive" and "buttress" tests); its ability to consolidate and "wrap" the rebar; and its finishability characteristics.

Fig. 7: Full scale 1.3 m (51 in.) thick mockup. Photo Credit: Robert Mattes

Fig. 8: Mock-up was heavily reinforced with 4 layers of heavy rebar, including 3 layers of closely spaced 35M (#9) rebar at the back of the work adjacent to a water proofing membrane. Photo Credit: Jimmy Wang

Each nozzleman began bench shooting (Fig. 10) the first lift, starting in the left corner of the wall of segment one, using the standard bench shooting procedures recommended in ACI 506R-16 Guide to Shotcrete. The nozzleman would insert and position the nozzle with the pipe extension into the 150 mm (6 in.) square openings in the reinforcing mat (along the inner wall face) on a consistent basis to reduce the shooting distance to the three back rows of 35M reinforcing bars and to the outer face of the wall (waterproofing membrane) (Fig. 11). The shotcrete stream was observed to impact the three layers of vertical reinforcing steel and waterproofing membrane at a high-impact velocity while a blow pipe was used to continuously clean the back reinforcing steel in front of the area about to be shot.

Fig. 9: Inside mock-up showing spliced 25M vertical reinforcing (inner wall face), spliced 3-35M vertical reinforcing (outer wall face), 15M holder bars and plastic waterstop.

Fig. 10: Nozzleman bench shooting mock-up with blow pipe operator working in tandem with the nozzleman.

Fig. 11: Nozzleman inserting entire nozzle tip and extension between square openings in the front mat of reinforcing steel. Shotcrete stream impacting three layers of vertical reinforcing steel and water proofing membrane at a high impacting velocity. Blow pipe being used to continuously clean the back reinforcing steel in front of the area about to be shot.

The nozzleman would systematically insert the nozzle into several square openings up and down while moving in a left to right direction to the centre of the mock-up. Three nozzlemen shot equal-sized block segments along the bottom half of the mock-up and, similarly, three additional nozzlemen shot the top half of the mock-up. The nozzlemen would hand off the nozzle once their segment was complete.

The nozzlemen began bench shooting the first lift of segments three and six from the far-right corner of the work, instead of at the transition between segments two and three (at bottom half) and between segments five and six (at top half), working back to segments two and five, respectively, which is standard practice to avoid trapping rebound into the corners of the work. Similarly, standard bench shooting procedures recommended in ACI 506R-16 were used. During shotcrete placement, the following took place:

- Nozzlemen would shoot approximately 500 mm (20 in.) high lifts.
- A blow pipe operator worked in tandem with each of the nozzlemen, removed overspray and shotcrete build-up from the reinforcing steel and rebound from the work (Fig. 12).
- An operator of a stiff rod immersion vibrator (Fig. 12) would start behind the nozzleman inserting the rod right to the back of the work to "lay down the bench" and provide supplementary consolidation of the shotcrete around the back-reinforcing steel bars to the outer wall face.

Fig. 12: An operator of a stiff rod vibrator would start behind the nozzleman inserting the vibrator to the back of the work to "lay down the bench" and provide supplementary consolidation of the shotcrete around the back reinforcing steel. Photo Credit: Leonard Crasta.

During regular and frequent stoppages in shotcrete placement:

- One to two blow pipe operators rigorously cleaned off any buildup of shotcrete and overspray from the reinforcing bars and removed rebound from the work.

Fig. 13: Supplementary consolidation provided by insertion of a long 40 mm diameter stiff rod vibrator into the back of the work. Photo Credit: Robert Mattes.

Fig. 14: Following use of stiff rod vibrator, shotcrete was being well consolidated and wrapping around the three outer 35M reinforcing steel bars. Photo Credit: Leonard Crasta.

Fig. 15: Nozzleman shooting the final finish coat of the mock-up. Photo Credit: Jimmy Wang.

Fig. 16: Final finishing of mock-up. Photo Credit: Jimmy Wang.

Fig. 17: Close up view of the finished mock-up.
Photo Credit: Mitchell Matais.

Fig. 18: Finished mock-up was cured using a spray on applied curing compound. Photo Credit: Jimmy Wang.

Fig. 19: Finished mock-up following stripping of the formwork after curing in air for 10-days.

- Two stiff immersion vibrators were inserted into the shotcrete to "lay down the bench" and provide supplementary consolidation to the back of the work adjacent to the waterproofing membrane and the outer vertical 35M reinforcing steel bars. Immersion vibrators were used extensively. One immersion vibrator had a curved rod to help consolidate shotcrete in previous lifts, and one immersion vibrator had a straight rod to enable reaching the outer wall formwork.
- Typically, the straight rod immersion vibrator would lay down the bench, which was followed by one or two blow pipe operators cleaning off the build-up of shotcrete and overspray on the reinforcing bars, and then the curved stiff rod immersion vibrator would provide additional shotcrete consolidation behind the blow pipe operator(s).

It was observed that by using the stiff immersion vibrators, shotcrete was well consolidated and wrapped around the three outer 35M reinforcing steel bars (Fig. 13 and 14). Final proof of the overall quality of the reinforcing steel encasement was confirmed when the work was cut open into blocks and a review of the adequacy of reinforcing steel wrap was completed.

Following bench shooting the work to the top of the mock-up and out to just cover the front reinforcing bars, a final finish coat layer was applied out to just beyond the shooting wires (Fig. 15) and then trimmed with a cutting screed to the shooting wires.

Wooden floats were used to close the surface then followed by a steel trowel finish (Fig. 16 and 17). The left half of block segment two and the left halves of block segments five, one, and four received a spray-on applied curing compound (Fig. 18), and the remainder of the mock-up surfaces were wet cured using water saturated burlap.

Upon a close-up review of the finished surfaces of the mock-up, the shotcrete mix incorporating 70% slag cement and natural cellulose fibre at 1.5 lbs/m^3 dosage displayed excellent finishability, with finished surfaces without any pulls or tears (Fig. 17). In addition, the mock-up's finished surfaces were found to be crack free (Fig. 19). These findings are attributed to using the natural cellulose fibre in the mix, which controls accumulation of bleed water near the surface and acts as a finishing aid as well as an internal curing aid due to the hydrophilic nature of the natural cellulose fibres.

Routine plastic shotcrete testing included temperature, slump (“as-batched” and “as-shot”), and plastic air content (“as-batched” and “as-shot”). The results of these plastic shotcrete tests are provided in Table 1.

The “as-batched” slump tested at discharge into the pump ranged between 75 mm and 110 mm (4.3 in.), and averaged 90 mm, which satisfied the specified slump of 90 mm +/- 20 mm at discharge into the pump. At these slumps, there did not appear to be any sloughing or sagging in the shotcrete placement. This finding was supported by the beehive test (Fig. 20), where shotcrete was applied onto a vertical plywood out to a thickness of about 220 mm (8.7 in.) before the shotcrete sagged. The “as-batched” air content tested at discharge into the pump ranged between 7.5% and 8.2%, and averaged 7.8%, which satisified the specified plastic air content of 7-10% at discharge into the pump. The as-batched slump was measured and showed that over 50% of the “as-batched” slump was lost during the shooting process as the mixture was designed with a high plastic air content, generally in the 7-10% range, to produce the “as-shot” air content ranged between 4.0% and 5.5%, and averaging 4.9%, which satisfied the specified “as-shot” air content range of 5 +/-1.5%.

Fig. 20: Beehive Test. Photo Credit: Mitchell Matias

Table 1. Plastic Shotcrete Properties

Mt. Pleasant Station Preconstruction Mock-up					
Load No.	**Temperature (°C)**	**“As-Batched” Slump (mm)**	**“As-Shot” Slump (mm)**	**“As-Batched” Plastic Air Content (%)**	**“As-shot” Plastic Air Content (%)**
1	24.0	110	20	8.0	5.0
2	21.0	85	5	7.5	5.5
3	23.5	90	40	7.6	4.0
4	23.2	75	20	8.2	5.0
Avg.	22.9	90	20	7.8	4.9
Spec.	10-25	90±20	-	7-10	5±1.5

The results of compressive strength of cores are provided in Table 2.

Table 2. Compressive Strength of Cores

Mt. Pleasant Station Preconstruction Mock-up			
Trial #	Compressive Strength of Cores (MPa)		
	7 Days	28 Days	56 Days
1	18.6	32.3	36.2
2	18.8	33.2	38.1
Avg.	**18.7**	**32.8**	**37.2**
Spec.	**-**	**-**	**35.0**

Compressive strength of cores tested at 56 days ranged between 36.2 and 38.1 MPa (5280 and 5530 psi), averaging 37.2 MPa (5400 psi), which satisfied the specified compressive strength of 35 MPa at 56 days.

The results of rapid chloride ion penetration of cores are provided in Table 3.

Table 3. Rapid Chloride Ion Permeability of Cores

Mt. Pleasant Station Preconstruction Mock-up			
Trial #	Rapid Chloride Permeability (Coulombs)		
	28 Days	56 Days	91 Days
1	1430	1059	-
Spec.	**-**	**-**	**1500**

Rapid chloride ion penetration of cores tested at 28 days and 56 days achieved 1430 coulombs and 1059 coulombs, respectively, which satisfied the specified rapid chloride ion penetration of 1500 coulombs within 91 days.

Using heat box analytics, the 70% slag shotcrete mixture's adiabatic heat development was found to reach a peak temperature of 56.2°C (133 °F) at 73 hours, which is less than the specified peak temperature in the center of the mass shotcrete walls of 70°C. B4Cast Modelling Software was then used to develop the thermal control plan by modeling the anticipated climatic environment and various boundary condition scenarios to safely dissipate the heat from these mass shotcrete walls, ensuring that the temperature differential between the near surface and the center of the mass shotcrete walls did not exceed the maximum specified temperature differential limit of 20°C. Thermal controls included limiting shotcrete placement temperatures and using three layers of R2.5 tarpaulins to cover the walls during the curing period.

Following mock-up construction, it was cut open into several block sections using a wire saw, and upon close evaluation, the quality of shotcrete in the stripped vertical ends (Fig. 19), around the reinforcing steel, and to the outer membrane were observed to be excellent (Fig. 21, 22, and 23).

Fig. 21: An example of a wire saw cut section of mockup showing excellent consolidation of shotcrete around the three layers of 35 M rebar at the back of the work and to the outer membrane.

Fig. 22: Another example of a wire saw cut section of mockup showing excellent consolidation of shotcrete around the three layers of 35 M rebar at the back of the work and to the outer membrane next to the embedded plastic water stop. Photo Credit: Jimmy Wang.

Fig. 23: An example of a wire saw cut section of mockup showing excellent quality of shotcrete at the transition between the shotcrete and the SCC using the StayForm Option 1 at the roof soffit with the keyway and plastic embedded water stop detail

An earlier study (Ref. 2) found that it was not possible to use the shotcrete process to construct the wall just below the roof soffit due to a keyway and embedded plastic water stop protruding outward along the underside of the roof. Poorly consolidated shotcrete was found, including significant voids behind the keyway and embedded plastic waterstop just below the roof soffit. Knowing that shotcrete was not an option here, CTS considered two alternative options to construct the wall just below the roof soffit behind the keyway and embedded plastic water stop. Options evaluated included the following:

1. Shoot shotcrete 300 mm (12 in.) short of the roof soffit so that there is a noticeable gap between the top of the shotcrete and the roof soffit. A 300 mm wide StayForm positioned 450 mm (18 in.) in from the front inner wall face (Fig. 24) was used to act as a receiving surface where shotcrete was applied directly to the StayForm and built out to cover the front mat of reinforcing steel. A final finish coat was then shot to the shooting wires and finished. At a later date, using a pressure pump technique, a self-consolidating concrete (SCC) mixture was pumped in behind the StayForm, filling the remaining 300 mm gap up to the roof.
2. Shoot shotcrete 300 mm short of the roof soffit so that there was a noticeable gap between the top of shotcrete and the roof soffit. At a later date, a suitable form was inserted along the front face of the wall and SCC was pumped between the top of shotcrete and the roof soffit filling the 300 mm gap along the entire wall thickness.

Upon review of the cut sections incorporating this detail, the overall quality of shotcrete at the transition between the shotcrete and the SCC was found to be excellent in Option 1 (using the StayForm) (Fig. 23). Option 2 revealed a minor, but notable cold joint observed in the cut section. CTS chose the StayForm Option 1 to construct the station walls along the underside of the roof soffit and behind the keyway and plastic embedded water stop.

QUALIFICATION OF SHOTCRETE INSPECTORS

The Mount Pleasant Station preconstruction mock-up was used as the practical component of the shotcrete inspector education and training program

[Insert Figure 24] *Fig. 24: A 300 mm wide StayForm positioned 450 mm. in from the front inner wall face used to act as a receiving surface to apply shotcrete out to cover the front rebar. Credit: Carl King.*

provided by the authors. The inspectors completed a review of the mock-up in advance of shotcrete application, and if there were any recommended adjustments to be made (such as fastening reinforcing steel or grout tube embedments), these were relayed to CTS for corrective action. The inspectors were each assigned to monitor a specific nozzleman during shooting. The following additional reviews were completed during construction of the mock-up:

- Shotcrete mixture behavior, such as mixture pumpability, shootability, adhesion/cohesion, reinforcing steel encapsulation, and finishability
- Equipment
- Nozzleman and crew technique

The inspectors were required to fill out and complete a detailed shotcrete inspection checklist report and provide comments on the acceptability of the work that was observed by the inspector. All inspection checklist reports were handed in and reviewed by the lead authors. At the conclusion of the mock-up phase of this work, a total of four shotcrete inspectors were qualified to provide full-time construction monitoring as part of CTS's quality control program during the construction phase of the work.

CONCLUSIONS

This article demonstrates how a total of 10 nozzlemen were prequalified to construct the station walls using the "hybrid" shoot and then vibrate shotcrete construction process. The work proceeded to construction based on the satisfactory mock-up results using the same equipment, mixture design, and qualified nozzlemen to construct the station walls. CTS was required by the designers to have the work monitored full-time by qualified third-party shotcrete inspectors. In addition, rigorous monitoring of temperature was completed by CTS as part of the thermal control plan to provide assurance that these mass shotcrete walls did not develop excessive temperature rise in the core of the element and that large temperature differentials resulting in thermal induced cracking were avoided (Ref. 4).

CTS received recognition of significantly 'decarbonizing' the construction process by using such high volumes of supplementary cementitious materials like slag cement, which are much more environmentally friendly than using more carbon-intensive General Use (GU) portland cement. Prior to extensive trials undertaken by CTS:

- Conventional low heat of hydration cast-in-place concrete mixes were typically designed with between 50-60% portland cement content
- A recent low heat of hydration shotcrete mix used in British Columbia incorporated 40% slag cement (Ref. 4)
- Conventional wet-mix shotcrete mixes were typically designed with up to 450 kg/m^3 of cementitious materials, at least 70% of which incorporated general use (GU) portland cement (i.e. portland cement production is known to have a high carbon footprint) (Ref. 3).

In summary, a considerable reduction in greenhouse gas emissions using 70% slag cement in the shotcrete mixture design can be achieved (Ref. 3). This level of cement replacement proved to be optimum, when combined with local materials, to provide performance benefits in reducing the heat of hydration, shrinkage, and permeability while minimizing short-term strength reductions.

A second paper to be published in an upcoming edition of *Shotcrete* magazine will provide details of the Mount Pleasant Station construction phase of this project.

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Shotcrete Pump Equipment: Reed | **Shotcrete Ready-Mix Supplier:** Innocon CBM
Shotcrete Testing Company: Qualitylinx | **Shotcrete Construction Inspectors:** WSP E&I Canada Ltd.
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Technical Support: Lloyd Keller, Dr. Dudley (Rusty) Morgan, and Dr. Lihe (John) Zhang

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., Mr. Radomski has extensive shotcrete consulting, inspection and testing experience North America wide, 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 and 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 MSc 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, F.ACI, *is the founder of Research and Development and Quality Control for EllisDon Construction in Mississauga, Ontario. He is fellow of 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 have been focused, over the last number of years, on Self Consolidation Concrete (ACI 237) and the prediction of formwork pressure. Shotcrete for structural installations and the control of exothermic heat generation with the utilization of high-volume supplementary cementing materials is also an area of research over the last few years.*

Dudley R. (Rusty) Morgan, Ph.D., F.ACI, *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 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.*

Daniel Sanchez *is a Professional Engineer with over two decades' background 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 of Barcelona, the Eglinton Crosstown LRT of Toronto or the Scarborough Subway Extension. Daniel holds a master's degree in civil engineering by the University of Granada, Spain.*

Laura Di Monte *is a mechanical engineer with Bell in Toronto, Canada. She worked as the Technical Project Coordinator for the Mount Pleasant Station project.*