2019 Outstanding Underground Project

Maryland Purple Line Plymouth Tunnel

By Nick Tabor and Norbert Fuegenschuh

The Plymouth Tunnel is a 1020 ft (311 m) sequential excavation method (SEM) tunnel located in Silver Spring, MD, that makes up a portion of the Maryland Transit Authority's (MTA) Purple Line light rail connecting the existing metro lines around Washington, DC. The Purple Line Transit Constructors (Flour/Lane/Traylor Joint Venture—PLTC) is the Lead Contractor with the Traylor personnel self-performing the excavation and lining work for the Plymouth Tunnel.

The Plymouth Tunnel was constructed using the SEM with shotcrete comprising both the initial and final support. The initial excavation was a 27 ft 4 in. (8.33 m) tall by 35 ft (10.7 m) wide horseshoe phased into a 20 ft (6.1 m) top heading and 7 ft 4 in. (2.23 m) bench. Most of the alignment runs under neighborhood streets with cover varying from 15 to 40 ft (4.6 to 12.2 m) above the crown. As both shotcrete applications are being included in the final design as a composite structure, the initial support shotcrete had to meet the 75-year design life criteria for permanent concrete. In addition to the early-strength requirements (1, 3, 6, and 12 hours), the ultimate 28-day strengths now had to be considered and the water-cementitious materials ratio (*w/cm*) had to be limited to less than 0.42. These requirements left little room for improving as the project progressed and required a quality application from the beginning.

EQUIPMENT SELECTION

To handle the 24-hour work cycle and the strict quality control requirements, a robotically applied wet-mix process was chosen. An ACT WiCoMix WM 1500 planetary mixer batch plant with a mixer capacity of 1.25 yd^3 (1 m^3) was installed on site and operated 24 hours a day for 1-1/2 years in all weather conditions. The batch plant was enclosed within a steel metal building with multiple heaters at critical points and heated wraps on the admixtures. A boiler and chiller were used in the winter and summer, respectively, and occasionally ice was required during the summer. The aggregate stockpiles were covered and had radiant heaters during winter and misters during summer.

Shotcrete was transported to the heading with three 7 yd^3 (5.5 m^3) Fiori DB 560 Ts with modifications to bring them into National Ready Mixed Concrete Association (NRMCA) compliance. The trucks were kept within the shade of the plant when possible and pretreated with boiling or chilled water as needed prior to batching. Shotcrete was primarily applied with two Meyco Potenza shotcrete robots, but a Meyco Oruga and hand application setup were also on site in case of an emergency. This equipment setup was used for the top and bottom heading during initial excavation as well as the shotcrete final liner.

Fig. 1: ACT WiCoMix WM 1500 Batch Plant with buildings and silos

Fig. 2: Plymouth Tunnel East Portal top heading excavation

SEM/NATM EXCAVATION

For the initial excavation of the Plymouth Tunnel, top heading rounds were taken in 4 to 5 ft (1.2 to 1.5 m) lengths. Support was comprised of a 2 in. (50 mm) flash coat followed by 13 in. (330 mm) of shotcrete with two layers of wire mesh. The shotcrete section was installed in two lifts to minimize sloughing and to eliminate the need to shoot through a second layer of reinforcing mesh. Due to safety requirements, no personnel access was permitted under freshly applied shotcrete until it was self-supporting (75 psi [0.5 MPa]). To minimize downtime due to this curing period after the first lift, the second layer mesh and shotcrete application was delayed until subsequent rounds or when multiple rounds could be shot at once. Based on the ground conditions, it was acceptable to delay the second 6 in. (150 mm) application to anytime within three rounds of the excavated face. The second layer of mesh installation could then occur during other work activities and was often concurrent with the drilling for the spiling.

A wire mesh reinforced shotcrete design was chosen for multiple reasons. One of the biggest reasons was the wire mesh served as a continuous grade indicator and served as a visual cue for the nozzlemen. Repeatedly having a flat reference ensured high points were not projected through the subsequent lifts and helped minimize any dips between the lattice girders. Providing this reference plane also served as the quality control check needed to ensure minimum thickness was applied. In addition, it eliminated the flexural strength testing which would have been required for fiber-reinforced shotcrete. As a bonus, removing the fibers from the mixture design minimized the material costs lost in the rebound and from the filling of over excavated areas. While there was still a waste factor with the mesh installation, it was trackable as a separate entity and easier to minimize than shotcrete rebound. Additional labor costs associated with the mesh installation were found to be minimal as the activity could be concurrent with other critical path activities most of the time.

Geology along the alignment varied from highly weathered saprolite and raveling sands to full-face bedrock with rock mass conditions. Due to the wide-ranging stability characteristics, the ground support sequence was determined daily based on the ground conditions. For the more stable face conditions, a 2 in. thick flash coat on the open ground was sufficient protection prior to the first wire mesh installation. In unstable geology, a center buttress (face wedge) was used and occasionally pocket excavation was needed. In these situations, the face was divided into thirds around the center buttress and each was exposed and supported with shotcrete sequentially. This limited the open time and prevented the looser material from raveling due to air slack. The quick shotcrete application lead to minimal settlements of the surface streets averaging less than 3/4 in. (19 mm) with no noticeable settlement to the surrounding structures. In total, over 5600 yd^3 (4281 m^3) were applied during the top heading excavation and 1000 yd^3 (765 m^3) in the bench.

During the installation, the excavation and shotcrete profiles were scanned with a survey suite provided by Amberg Systems. This consisted of the Amberg Tunnel software with a Leica TS-16 and Faro Focus 3D scanner. The software allowed for the comparison between the theoretical profiles, as-built excavation, and shotcrete lifts. These profiles captured and quantified the excavation over-break and actual applied shotcrete thickness. This helped the nozzlemen to maintain a final shotcrete smoothness within +/- 1 in. (25 mm)along the tunnel. With the thickness as-built records and tight smoothness criteria, PLTC was able to take

Fig. 3: Top heading flash coat application in mixed face conditions

Fig. 4: Completion of initial lining after excavation

advantage of the overbreak volume and eliminated an additional 2 in. shotcrete regulating layer from the initial lining. This minimized the waste normally lost to the overbreak, saved the cost and time for the additional 2 in. application, and provided greater tolerance for the final installation.

Beton- und Monierbau USA, Inc. (BeMo) was a key partner to the successful completion of the tunnel. BeMo provided key foremen that not only served as experienced eyes in the field but also as shotcrete trainers and nozzlemen. The key foremen worked with the crews to provide operational experience during excavation works, ground support measure installation, and shotcrete application. They were on site for the entire installation and assisted with all critical operations.

Shotcrete on PVC Mockup

After completion of a form-and-pour invert (17 sections with single lengths of 60 to 70 ft [18 to 21 m]), the design called for a polyvinyl chloride (PVC) waterproofing membrane followed by an additional 13 in. of structural concrete with two layers of wire mesh reinforcement and at least 2 in. of polyfiber-reinforced concrete on the intrados. Due to the short tunnel length and multiple geometry changes for service utilities and permanent ventilation fans, the upfront cost of the form-and-pour formwork was prohibitive. The shotcrete equipment was already on site and the team had already demonstrated their ability to control the profile to meet the stringent final lining criteria. A proof-of-concept mockup was constructed within the tunnel to demonstrate the feasibility as well as to test various methods for supporting the PVC membrane. The PVC membrane was installed from the springline past the overhead arch along 15 ft (4.6 m) of tunnel within an area of over excavation. The proposed supporting measures and mesh were installed per the tunnel design and 6 in. of shotcrete was applied. Cores were taken through the different sections and the gap was measured between the PVC membrane and the two shotcrete layers. These gaps resulted from the "pillowing" inherent with the PVC installation but could be drastically reduced based on the installation means and methods. Ultimately, the support points for the waterproofing were tightened up to 2 ft (0.6 m) on center and instead of chairs or bricks, plastic continuous upper beam bolsters were used to push back the membrane. These additional measures provided the best cost and quality benefit without dragging out the waterproofing installation.

Shotcrete Final Lining

BeMo was also instrumental in developing an application approach that used lattice girders to provide initial support to the wire mesh and provided a rigid shell to push back the PVC membrane. Lattice girders were erected at 5 ft on center and supported with longitudinal No. 5 (No. 16M) reinforcing bars at 2 ft on center. While serving in a structural capacity, the No. 5 bars also provided rigidity to the thinner mesh profiles to minimize vibrations and ensure good encapsulation. In select overhead areas where there was a gap larger than 4 in. (100 mm) between the girders and the membrane, an additional thin layer of non-structural W4/W4 welded wire fabric was installed directly against the membrane and blocked off the girders with chairs. This provided a supporting matrix against the membrane and facilitated the "buildup" of shotcrete. The structural wire mesh sections were installed between the girders and bolsters were used to push back/support the PVC membrane. A 6 in. layer of shotcrete was applied below the springline and over the crown along the lattice girders. This formed a series of overhead arches that could be used to support the remaining shotcrete. Once the arches had reached sufficient strength, the resulting bays were filled. The front of the girders were cleaned off and the second layer of mesh was installed. The second lift of shotcrete was applied to roughly 1 in. past the wire mesh. Note the mesh installation had to be carefully aligned and surveyed as it serves as the grade indication for the nozzlemen when they were approaching the desired profile.

For the final 2 in. polyfiber-reinforced layer, the shotcrete gun finish for the on-site mixture was sufficient from the crown to within 6 ft (1.8 m) of the walkway. From the walkway to 6 ft up the wall, a fine gradation mixture, MS-W1 from King Packaged Materials, was used. To achieve the desired

Fig. 5: Spraying secondary liner overhead arches on PVC waterproofing membrane

Fig. 6: Secondary liner overhead arches built up on lattice girders

smoothness and tight tolerances with the Potenza, a grid of fiberglass grade pins were installed on an offset 5 by 5 ft grid and at 1 ft (0.3 m) on center along the smoothing layer demarcation line. The grade pins were surveyed and cut to 1/2 in. (13 mm) inside the final profile.

SUMMARY

The Plymouth Tunnel was a unique opportunity to highlight the multiple benefits of shotcrete. Initial support shotcrete was able to be batched on site and provided quick support to the excavated face. The initial support shotcrete could be designed and quality controlled to meet permanent concrete standards and be included in the final design. Overbreak was recorded and the profile was controlled to minimize waste, expedite construction, and enhance the final tolerances. Additional supporting methods were evaluated in a full-scale mockup and used to enable the overhead robotic application of shotcrete on a PVC liner with minimal remedial grouting. The shotcrete equipment and workforce for the initial excavation were able to construct the final lining and still meet the watertightness and structural requirements of the permanent structure while leaving behind a unique aesthetic that is sure to be replicated soon.

Fig. 7: Spraying secondary liner bays between arches

Fig. 8: Plymouth Tunnel shotcrete final liner with form-and-pour invert

Fig. 9: Initial shotcrete application on PVC liner

2019 OUTSTANDING UNDERGROUND PROJECT

Project Name
Maryland Purple Line Plymouth Tunnel

Location
Silver Spring, MD

Shotcrete Contractor
**Traylor Bros., Inc.*
(JV partner in the Purple Line Transit Constructors)**

Architect/Engineer
Mott MacDonald

Material Supplier/Manufacturer
LafargeHolcim (cement), Sika (silica fume), Mapei* (admixtures)

Equipment Manufacturer
Advanced Concrete Technologies

General Contractor
Purple Line Transit Constructors (Fluor/Lane/Traylor JV)

Project Owner
Maryland Transportation Authority/ Purple Line Transit Partners

*Corporate Member of the American Shotcrete Association

Nick Tabor *is a Project Engineer with Traylor Bros., Inc. He worked with Traylor Bros. throughout his time at Purdue University, Lafayette, IN, where he received his BS in civil engineering in 2011 and obtained his professional engineering license in 2015. Tabor has been involved with many projects across the underground, heavy civil, and estimating divisions with experience in both design-build and public-private-partnership contracts. His recent experience includes the Blue Plains Tunnel, a 24,000 ft (7300 m) long, 26 ft (8 m) diameter EPB TBM CSO tunnel constructed in soft ground, and the Plymouth Tunnel, a 1020 ft (311 m) long, 27.33 ft (8.33 m) by 35 ft (11 m) horseshoe SEM/NATM transportation tunnel constructed in mixed face conditions. Tabor has experience with multiple facets of heavy civil underground construction from design development, coordination, and permitting through site setup, excavation, concrete/shotcrete works, and closeout. He is a member of UCA of SME, ASCE, and ACI, and serves as a professional mentor for the University of Maryland's Engineers without Borders.*

Norbert Fuegenschuh *attended the University of Technology, Graz, Austria, where he received his master's degree in civil engineering in 1989. He joined Beton- und Monierbau, now BeMo Tunnelling (short BeMo), located in Innsbruck, Austria, in 1990. Fuegenschuh began his professional career in the estimating department. After 1 year, he was transferred to Germany, where he spent a total of 10 years on subway and tunnel construction sites in charge of varying positions as quantity surveyor, deputy site manager, and site and project manager. In 2001, he became the Tunnel Manager at the Russia Wharf Tunnel project in Boston, MA. This was one of the first projects in the United States where a sprayed concrete inner lining was installed. He spent 2005 to 2011 in Sweden as Project Manager on two different tunnel projects and became BeMo Tunnelling's Area Manager for Scandinavia. Since 2011, he has served as President of Beton- und Monierbau USA, Inc., operating out of an office in Vienna, VA, and responsible for projects in the United States and Canada. Fuegenschuh has 30 years of experience in SEM/ NATM tunneling, including shotcreting works for tunnel primary and secondary linings. He is member of UCA of SME, the Tunneling Association of Canada, DFI's Underground Committee, and he also represents Austria in the International committee of the RETC.*

The latest projects with BeMo's involvement in North America include John Hart Generating Station in Campbell River, BC, Canada; China Town Station in San Francisco, CA; Quarters Tunnel LRT Project in Edmonton, AB, Canada; SEM cavern at Regional Connector in Los Angeles, CA; Plymouth Tunnel on Purple Line in Maryland; and Cross passages at Purple Line Westside extension, phase 1 in Los Angeles, CA.