Design and Construction Aspects of Pneumatically Applied Concrete Final Tunnel Linings

Recent Experience at the East Side Access (ESA) Project in New York

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ABSTRACT

The East Side Access Project (ESA) involves the construction of geometrically complex underground structures including a large number of caverns and bifurcations. Initially conceived as dual lined structures with either traditional concrete or shotcrete final linings (SFL), construction economy, advances in concrete placement technology and scheduling among others led to a wide use of what is referred to as freeform or pneumatically applied concrete (PAC) for the construction of tunnel final linings. PAC is a method of applying concrete without using formwork, where a wet mix concrete is pneumatically installed to encase reinforcement to full lining thickness. PAC has been widely adopted at ESA well beyond initial expectations. The paper addresses the design and construction aspects of the PAC method and contrasts it to traditional SFL lining placement. The experience made provides guidance for future PAC and SFL applications.

THE EAST SIDE ACCESS PROJECT AND USE OF FREEFORM CONCRETE

The Long Island Rail Road (LIRR) currently transports commuters from Long Island into Manhattan, terminating at the already congested Penn Station on the west side of Manhattan. Once completed, the ESA Project will provide LIRR commuters direct access to the east side of Manhattan underneath Grand Central Terminal. The ESA Project will help alleviate the congestion at Penn Station, which currently accommodates New Jersey Transit, Amtrak, and LIRR lines; reduce travel time for LIRR passengers traveling to the east side of Manhattan and facilitate connections to the New York City Transit (NYCT) Subway System and Metro North Rail Road.

The construction includes mining and lining of new tunnels and facilities under Manhattan and Queens. The tunnels run from Queen's Sunny Side Yard through the existing 63rd St. Tunnel, underneath Manhattan's Park Avenue until termination at 37th Street. Differing types of tunneling methods and final lining systems are being used depending on the ground conditions, geometry and size of the excavation, site constraints and functional requirements. Mining of the Queens segment of the ESA Project involved soft ground tunneling by pressurized face tunnel boring machines, cut and cover construction, and conventional tunneling. The Manhattan segment of the ESA Project involves mining in hard rock by tunnel boring machines, drill and blast, and road header.

In Manhattan, cast-in-place concrete linings are mainly used in structures with constant cross section and of sufficient length to enable repeat use of formwork systems; these include running tunnels, vertical final lining walls and interior structures of multi-level structures and shafts. Structures with complex and variable geometry were designed for the application of shotcrete final lining where complicated and custom-made formwork would otherwise be required (see Figure 1 for an example of geometrically varying structures within the Manhattan alignment). The arches of the multilevel structures were also designed for the use of shotcrete final lining. The design of shotcrete final linings typically involves the use of lattice girders to support the steel reinforcement and assist in controlling the profile/geometry of the tunnel cross section and is applied in layers placed in distinct multiple passes to build up the concrete thickness of the final linings (Gall et al., 2004). It requires a high level of application skill, workmanship and a rigorous quality control process.

The typical sequencing as foreseen in the design and specifications for SFL at ESA involved: (1) installation of lattice girders at 1.5 m (5 feet) centers with a rebar reinforcement mat placed against the waterproofing membrane at the extrados side of the girders, and partial spraying of the lattice girders, (2) shotcreting of an in-fill first layer between the lattice girders, (3) shotcreting of a second layer, (4) installation of rebar reinforcement on the intrado side of the lining and then (5) installing a final shotcrete layer to provide the minimum cover over the reinforcement. The number of shotcrete layer installations would depend on the total design thickness of the final lining. All shotcreting was specified to be carried out by robotic equipment. Figure 2 illustrates the installation of SFL at the Weehawken Tunnel using shotcrete robot.

In order to overcome the sequencing limitations of shotcrete final lining placement and avoid use of complex and expensive, custom made formwork for cast-in-place concrete (CIP) applications PAC was introduced to the ESA project. This method of application was initially implemented via a value engineering proposal presented by one of the contractors and later incorporated into the Contract Documents per request of Metropolitan Transit Authority Capital Construction (MTACC) as an alternative to cast-in-place construction subject to the successful demonstration of preconstruction testing. Contract documents were laid out such as to identify areas of PAC and SFL application by structure where these could be used as alternatives to traditional CIP concrete. Specifications entailed the rigorous pre-construction requirements for placement quality and skill of highly experienced nozzlemen for both SFL and PAC. While the reinforcement design for CIP and PAC linings is the same, the design portrayed in the contract for SFL was based on the use of lattice girders as installation means and reinforcement sizing to be compatible with the spraying process.

The use of PAC became widespread on ESA and was used for the construction of the final lining of the large cut and cover structure in Queens which was designed as a structural steel frame encased in cast-in-place concrete. The final lining of the conventionally mined tunnel section directly below Northern Boulevard tunnel was originally designed as a reinforced cast-in-place concrete structure with encased steel ring girders with a lining thickness of almost 80 cm (2.5 feet) and was placed using PAC. In summary the following structures were lined with PAC final lining in Manhattan:

- Vertical shaft walls
- Inclined escalator shafts
- Fish mouths between cross passages and bored tunnels
- Wye caverns where cross section changes continuously
- Cross passages and other restricted locations

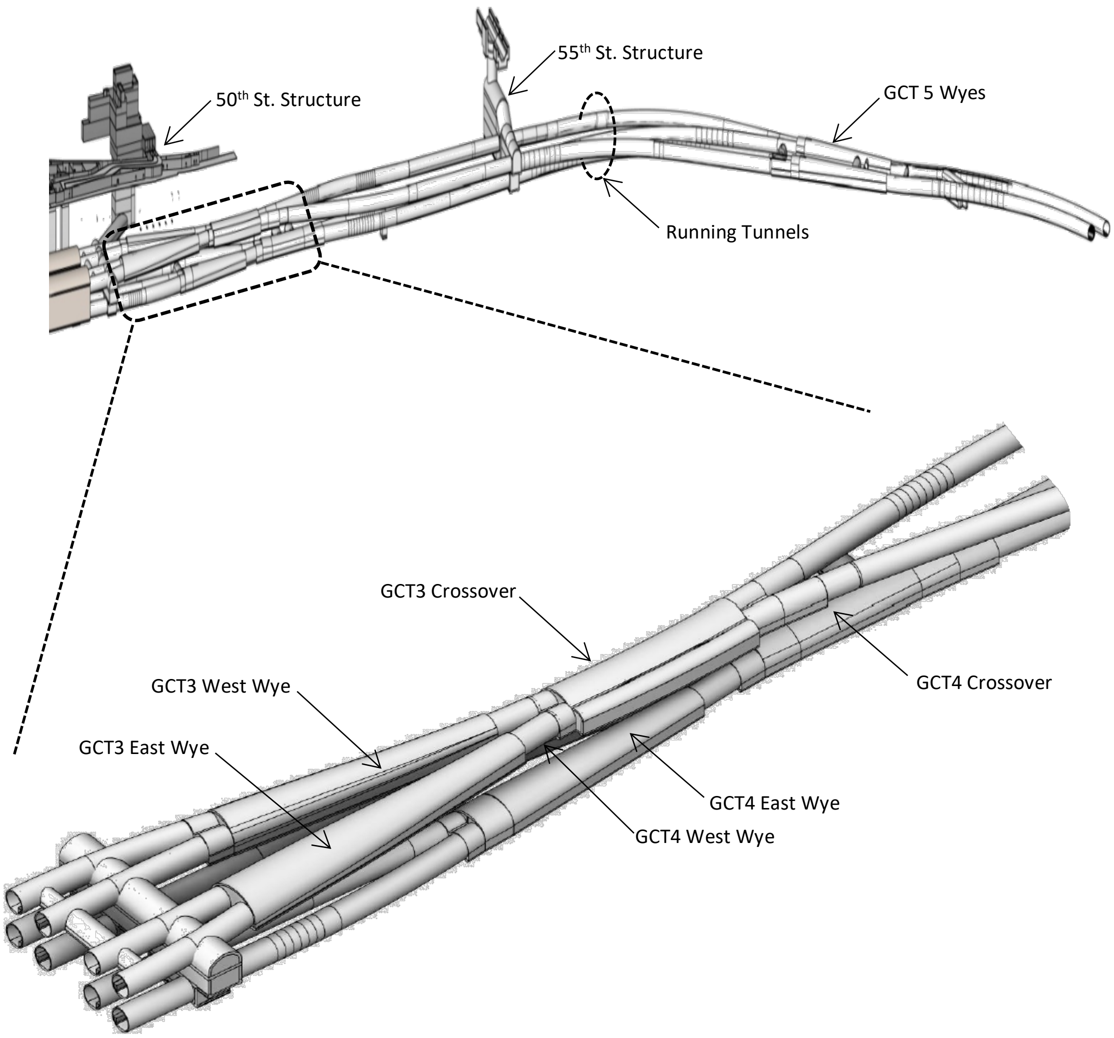

Figure 1. Layout of the ESA structures in Manhattan (Example: Contract CM006)

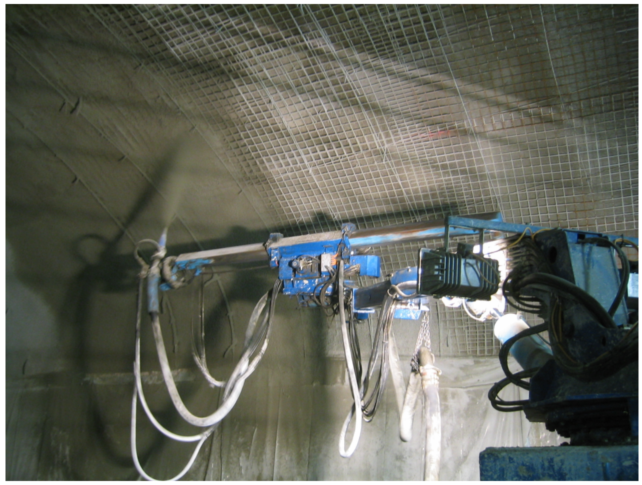

Figure 2. Typical Shotcrete Final Lining installation (Weehawken Tunnel in New Jersey, ca. 2004)

PAC AND ITS ADVANTAGES

PAC involves the application of structural concrete utilizing compressed air as the means for achieving consolidation, compaction, and a uniform distribution of concrete constituents. The end product is a Portland Cement Concrete (PCC) capable of achieving conventional and high strengths, while maintaining or exceeding required end properties by design. Commonly referred to as Shotcrete, the process used at ESA uses the wet mix process, wherein materials are delivered in a wet, pre-mixed state ready to place. Materials are pumped wet to the nozzle where air is added at high pressure to achieve the required spray pattern and velocity for the concrete application.

PAC is shotcrete placed by hand whereas Shotcrete Final Linings typically use robotic equipment to place shotcrete but both involve the following:

- METHOD – Shotcrete is a method of casting concrete in place pneumatically.
- APPLICATION - Shotcrete may be applied by the "Dry Mix" or "Wet Mix" processes.
- WET MIX – Shotcrete is typically applied by the wet mix process where ready mix concrete is pumped to the nozzle and air is added to create the velocity and spray pattern needed to encase reinforcement properly and completely on new walls, pilasters, and beams, as well as other similar structural concrete applications.
- DRY MIX – Gunite is typically applied by the dry mix process where sand and cement are mixed dry and conveyed by air to the nozzle and water is added to hydrate the materials in a very dry state to repair structural concrete surfaces of buildings, bridges, dams, and tunnels.
- DESIGN MIXES - Concrete Mix designs for Structural Wet Mix Shotcrete processes are created for use in conventional ready mix supply of wet materials as well as onsite delivery and mixing or batching of dry materials.

PAC excels in tunnel applications where conventional forming methods are difficult logistically as well as costly to construct. Where conventional methods use large, heavy, and in most cases steel forms that have limited flexibility in final position, PAC finds its most effective uses. The benefits that the use of PAC brings include no need to engineer, fabricate, install and remove a form system in a restricted underground space which means the forms are also not going to block the tunnel during concrete placement operations. Scaffolding is needed but typically there is a need for scaffolding for the lathers and in any case scaffolding is lighter and easier to transport and install than a form system.

In the many different structures that attach to a TBM heading, PAC has proven effective for caverns, wyes, cross passages, vent shafts, air plenums, ancillaries, inclined well ways, TBM crossovers and intersections “fish mouths”, that render uniform linear applications venerable to customization requirements. PAC may be “free formed” using various wire and steel rail methods to achieve literally any final shape and limit required. A good example is the “fish mouth” intersection of two tunnel headings or a tunnel heading and a cross passage or crossover. In all cases, these features prove difficult in their requirements for any method of concrete placement. PAC affords a monolithic placement while allowing the Contractor to achieve the needed variations in conforming to the dynamic conditions of the project which would not otherwise be achievable with a fixed forming system (Thompson and Federico, 2013).

PAC SPECIFICATION AND PRECONSTRUCTION TESTING

The successful application of PAC on the ESA Project necessitated the development of a technical specification specifying the requirements for the use of PAC and the implementation of a PAC Approval Procedure.

The specification includes requirements for: quality control, nozzlemen and supervisor qualifications, mix design and preconstruction testing, structure mock-up, construction test panels, submittals and shop drawings, materials, equipment, preparation of surfaces to receive PAC, application, construction tolerances and curing.

A PAC Approval Procedure was established on the ESA Project to ensure that the Contractor complies with all contract requirements for PAC application and the relevant code requirements are met; safety and administrative procedures are followed and to assist in the review and approval process of PAC by the MTA Code Compliance Unit (MTACCU), Construction Manager (CM) and General Engineering Consultant (GEC), see Figure 3.

The PAC specification at the ESA Project permits the Contractor to use Pneumatically Applied Concrete (PAC) subject to satisfactory completion of preconstruction testing. The PAC specification specifies that preconstruction testing shall be performed in compliance with the requirements of New York State Building Code (NYSBC) Section 1914 and ACI 506.2 - Specification for Shotcrete. Preconstruction testing required the Contractor to spray preconstruction vertical and overhead test panels (see Figure 4) and a pre-construction field trial structure mock-up (see Figure 5). Preconstruction test panels were sprayed, cut and cored prior to the mock-up construction and only ACI certified nozzlemen were permitted to spray the panels. The preconstruction test panels included typical reinforcement patterns representative of the areas where PAC was proposed by the Contractor. The acceptance criterion for the preconstruction test panels was based on the complete filling of zones behind the reinforcement and the absence of voids. The testing procedures were in compliance with ACI 506.2.

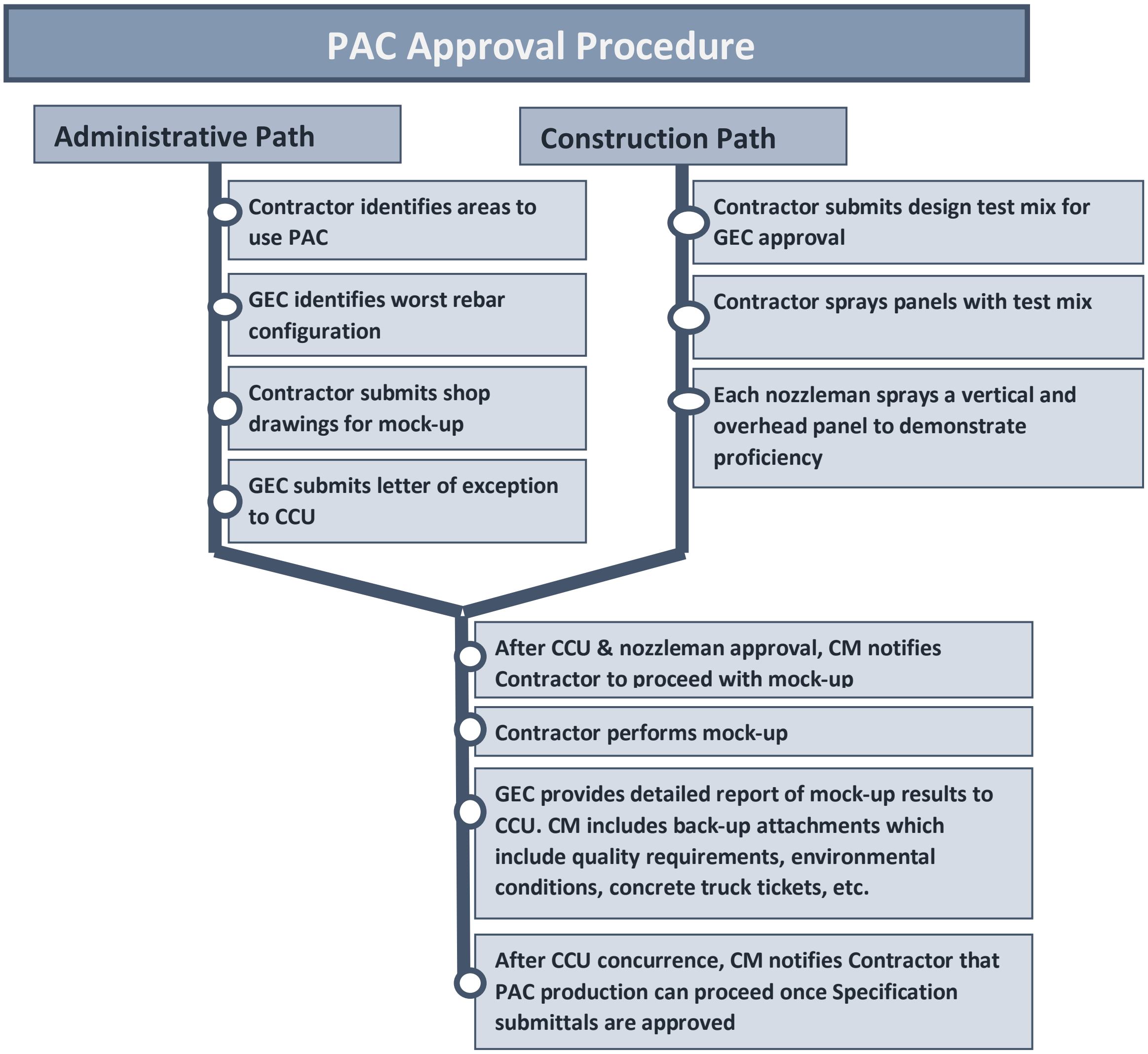

Figure 3. PAC Review Process

To comply with the specific requirements of New York State Building Code Section 1914.5 and the PAC specification, the preconstruction field trial mock-up configuration captured the thickest and most congested areas of structural reinforcement to be placed using the PAC method. The mock-up represented the most congested reinforcing configuration and the required concrete thickness and waterproofing system for the structures where the Contractor proposed to use PAC. The mock-up was used to simulate the Contractor's proposed means and methods that would be applied in the field. The mockup was divided into areas to be able to evaluate the results of each nozzlemen for both vertical and overhead applications. Only nozzlemen that demonstrated acceptable results in the preconstruction test panels were used in the mock-up. After PAC placement was completed on the mock-up, an inspection was then performed by the GEC and the CM to evaluate the mockup test results in accordance with the Contract Specifications and the NYSBC. The inspection included evaluation of the quality of the surface finish, encapsulation around reinforcement and encasement of waterproofing components, which included waterbarriers, re-groutable hoses, and remedial grouting pipes (see Figure 6).

For locations where PAC is applied, the specifications required that the finished concrete shall consist of a dense and uniform concrete with a rubber float or equal finished. This was demonstrated in the PAC mock-up and achieved during actual field applications.

Surface preparation prior to the application of PAC and the time lag between lifts of PAC application to construct the full final lining thickness of a structure need to be evaluated during preconstruction testing and closely monitored in the field since they significantly impact the quality of PAC construction. Figure 7 shows the application of PAC at the fish mouth at cross passages and the GCT3 cavern. Surfaces that are to receive PAC shall be cleaned of all loose material by using a combination of water and high velocity air. Surfaces shall be moist from the time cleaning is completed until the PAC is applied. In accordance with the ACI 506.4R procedures to evaluate the quality and properties of in-place concrete, a pull test to measure the bond strength between multiple lifts of PAC is recommended. ACI 506R Guide to Shotcrete recommends that pneumatically projected concrete develops a minimum tensile bond strength of 100 psi.

The ESA Project specifications state that the wet-mix process shall be used for PAC application and that the design mix shall achieve a minimum compressive strength of 5,000 psi at 28 days. The mix design shall be confirmed by strength tests on specimens taken from unreinforced preconstruction test panels at 72 hours, 7 days and 28 days. The specifications require that a minimum of one construction test panel shall be provided by the Contractor for every day of concrete placement and compressive strength tests shall be completed at 7 days and 28 days.

Similar to cast-in-place and shotcrete final linings, tolerances for PAC construction shall conform to ACI 117 and/or project specifications.

Figure 4. Preconstruction vertical (a) and overhead (b) test panels

Figure 5. Pre-construction field trial PAC mock-up hand spraying of vertical walls

Figure 6: Encapsulation of reinforcement, embedments and encasement of waterbarrier (on right lower side)

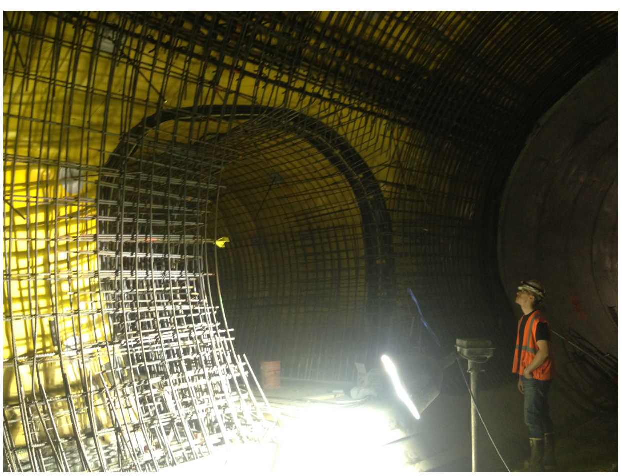

Figure 7. The fish mouth of a running tunnel cross passage (a) before and (b) after PAC application.

WATERPROOFING CONSIDERATIONS

In the ESA Project, underground structures are required to be watertight. A waterproofing system consisting of a synthetic membrane (PVC), geotextile/geodrain, waterbarriers, remedial grouting pipes, contact grouting pipes and terminal boxes has been used to prevent intrusion of groundwater into the structures. PAC as a structural final lining has been applied successfully against the waterproofing system. The reinforcement was secured in place by means of so called BA-Anchors, which allow for watertight penetrations of the PVC waterproofing membrane. At locations where the Contractor elects to use PAC as well as SFL, all waterbarriers used as part of the waterproofing sectioning system are equipped with re-groutable hoses to ensure adequate embedment of the waterbarriers with the PAC. After the concrete lining has gained its 28-day compressive strength, grout is injected through the re-groutable hoses to fill any voids between the waterbarrier and the PAC final lining. Similar to cast-in-place and shotcrete final linings, contract grouting is required when PAC is used to fill any voids between the waterproofing membrane and the concrete final lining. This contact grouting, unlike the one in roof sections in cast-in-place final lining installations, is not limited to roof sections only, but a radial and more frequent distribution of grouting ports and pipes around the crown and above springline was implemented for this purpose. Injection of low viscosity cementitious grouts between the final PAC lining and the membrane assures a tight contact between the initial and final lining.

PAC WORK PLAN

The Contractor shall submit a PAC Work Plan for each type of structure where PAC is to be used as a final lining. The plan shall include: list of materials and equipment to be used, installation procedures and concrete placement sequence, construction tolerances and required cover for reinforcement, methods of controlling concrete thickness and geometry of the structure, testing during construction, provisions for temporary construction joints in the case that PAC placement is stopped at an unplanned location, calculations for any auxiliary support measures to secure the reinforcement by BA-Anchors in place and inspection procedures/checklist for surface preparation, waterproofing system, reinforcement and embedded items (pipes, conduits, steel sections). The PAC work plan shall also include details at interfaces of structures and where additional measures are needed due to a change in geometry, reinforcement configuration and surface substrate.

SURFACE FINISH

Both SFL and PAC surfaces can be screeded, trowel finished or receive a rubber float finish. The final quality can very well compete with a cast-in-place concrete surface. In the initial applications PAC surfaces were rubber float finished to a high surface finish quality. Figure 8 shows columns constructed by PAC in one of the Queens contracts. To increase economy however and borrowing from the SFL specification section a sprayed shotcrete finish was chosen with trowel finish quality only specified to 8 feet above the safety walkway. Where sprayed finish surface quality is acceptable a required flatness/smoothness criterion, which calls for a deviation of not more than 2.5 cm (1 inch) was specified.

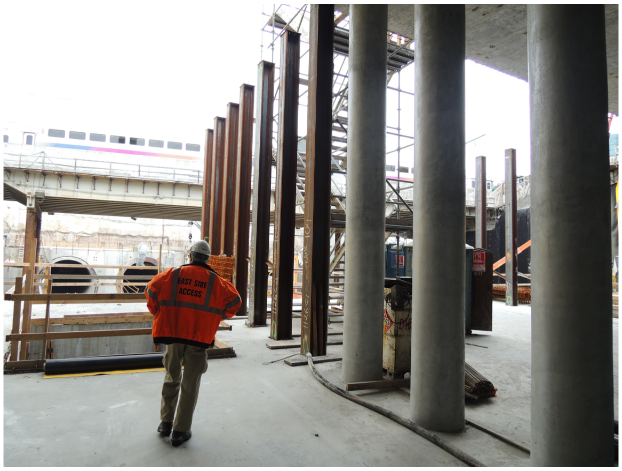

Figure 8. Columns constructed using Pneumatically Applied Concrete

Figure 9. Cross passage fishmouth interface at the GCT 4 Facility

CONCLUSION

Based on general trends in the application of shotcrete for final linings and as demonstrated at ESA it is apparent that shotcrete presents a viable alternative to traditional cast-in-place concrete. The product shotcrete fulfills cast-in-place concrete requirements and is nowadays viewed as equal in terms of its durability and therefore long-term performance. The PAC method was applied in non-uniform cross sections, shafts and other areas where the installation of a form would be problematic. Design and engineering, as well as application procedures, can be planned such as to lay the basis for a high quality product. However, excellence is needed in the application itself. Skilled nozzlemen have to ensure a high degree of workmanship through formalized training, experience and quality assurance during application.

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