SHOTCRETE Innovations

Andy Thompson, Vice President of Mott MacDonald in New York, and Frank Townsend, Vice President of Operations for specialty contractor Superior Gunite, discuss innovations and issues that have been encountered when using sprayed concrete for the installation of permanent structural linings for non-uniform openings in underground construction

HISTORICALLY, PERMANENT concrete linings for underground structures have been installed using form and pour methods, but the use of shotcrete or sprayed concrete for structural linings is becoming increasingly common. Although cast in place methods are well proven, they do have their downsides, especially where non-uniform shapes are required.

Although form and pour methods can be used for virtually every combination of shapes and spaces, there are drawbacks to its use especially when non-uniform cross sections and junctions etc. are required. Designing and installing custom built formwork is time consuming and depending on project logistics can cause pinch points in the schedule. As Clients strive to manage the scarce capital they have to manage existing and build new facilities, designers and constructers are increasingly being challenged to minimize the excavation and lining quantities. This brings new challenges to the use of cast in place concrete due to the complex nature of the shapes being designed.

The use of shotcrete or sprayed concrete for the installation of the permanent structural lining for non-uniform openings is a well-established process, but in the last few years the boundaries of its use, especially in the US have been stretched. Mott MacDonald in conjunction with Superior Gunite have been at the forefront of expanding the use of this application method in the underground environment.

PAC in use

Freeform concrete

So what are the benefits of the use of freeform concrete linings, how do they differ from shotcrete final linings, and what are the potential drawbacks?

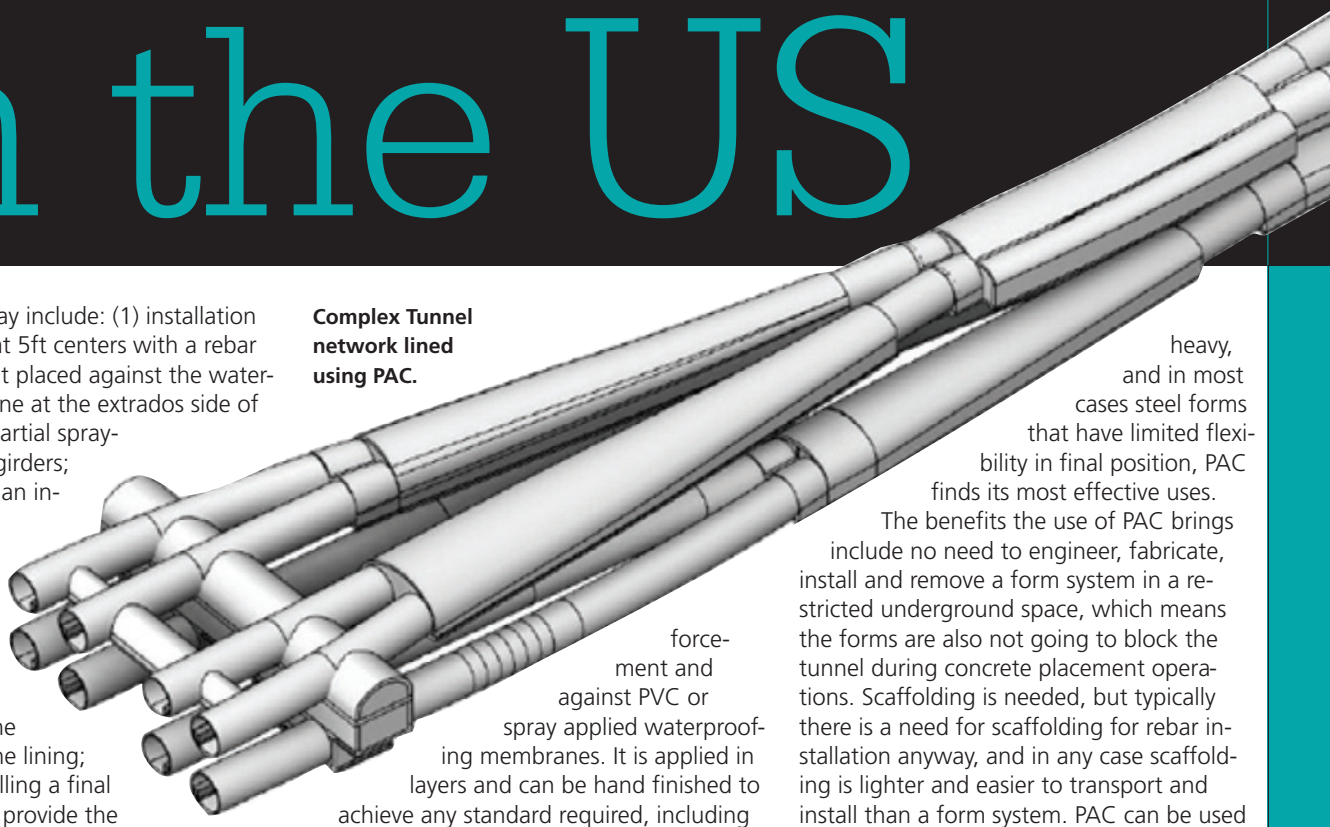
Freeform concrete, also referred to as Pneumatically Applied Concrete (PAC), as developed for use on many of the major capital projects under construction in New York, involves the application of structural concrete utilizing high velocity pneumatic projection from a nozzle as the means for achieving consolidation, compaction, and a uniform distribution of the concrete constituents.

The end product is a one half inch, minus Portland Cement Concrete (PCC), capable of achieving conventional and high strengths, while maintaining or exceeding required end properties by design. Materials are pumped wet to the nozzle where air is added at high pressure to achieve the required spray pattern and high velocity for the concrete application. This application mimics ACI 506 and sites the ACI specification as a reference.

How is this different to a shotcrete final lining (SFL)? A typical SFL lining 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 to build up the concrete thickness of the final linings. Reinforcement in such applications is usually small bar diameter (five or less) and well-spaced out, to minimize the opportunity for shadowing of the shotcrete around the girders and rebar.

It requires a high level of application skill, workmanship, and a rigorous quality control process. It is also increasingly being installed using robotic spraying, which therefore limits the finish that can be achieved to that of a nozzle finish. For example, a typical se-

in the US



Complex Tunnel network lined using PAC.

quence for SFL may include: (1) installation of lattice girders at 5ft 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 infill first layer between the lattice girders; (3) shotcreting of a second layer; (4) installation of rebar reinforcement on the intrados 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.

Freeform concrete or PAC, by contrast, is utilized with the same rebar design that would be used for a form and pour lining and no specific provisions need to be made to accommodate its use. It can be used around extremely heavy and congested reinforcement and against PVC or spray applied waterproofing membranes. It is applied in layers and can be hand finished to achieve any standard required, including textured architectural finishes. It does however require highly skilled nozzle men and support crews to ensure a safe and high quality finish is achieved as well as an extremely rigorous quality control process both before application and during.

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 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 rebar installation anyway, and in any case scaffolding is lighter and easier to transport and install than a form system. PAC can be used with or without waterproofing, be it sheet membrane or spray applied, although enhanced QC will be required for sheet membrane systems especially in overhead applications to ensure the membrane is tight against the substrate.

PAC has been successfully used for caverns, wyes, cross passages, vent shafts, air plenums, inclined escalator shafts, TBM crossovers and tunnel junctions, all of which are locations that render uniform linear applications vulnerable to customization requirements. In these locations, PAC affords a monolithic placement process to be utilized while allowing the Designer and Contractor to achieve the needed variations in conforming to the ever changing conditions of a project, which would not otherwise be achievable with a fixed forming system. For a tunnel system PAC is an ideal placement method for the many and varied geometries.

While PAC is extremely versatile it is not a process that can be used in all locations, for example, repetitive uniform TBM lining operations are better served using a traditional form and pour approach as the rate of placement of PAC can never equal that of a form.

As noted above the use of PAC requires a rigorous Quality Control Process. For exam-

Typical example of PAC lined structure

Preconstruction vertical (a) and overhead (b) test panel

Pre-construction field trial PAC mock-up and hand spraying of vertical walls

Encapsulation around reinforcement, embedments and encasement of a waterbarrier (on right lower side)

ple when PAC was introduced to a recent project in New York it became clear that additional measures would need to be included in the Quality Control process, both to ensure a safe and high quality installation, but also to satisfy the requirements of the New York State Building Code (NYSBC). The NYSBC includes requirements that need to be met to permit the installation of shotcrete as a structural component. These requirements include #5 rebar as the maximum size of rebar to be used, a "6 inch" minimum rebar spacing and a prohibition on the use of full contact lap splices. Crucially, however, the NYSBC includes a provision for a waiver to these requirements should the designer be satisfied that full encapsulation of the designed rebar can be achieved. So to satisfy this requirement the following process was put in place.

In addition to vertical and overhead test panels for proving the shotcrete mix design to be used, a full size preconstruction mockup of the lining was required to be undertaken, utilizing the approved mix designs and the equipment proposed for use in the works. Working with the designer, the most heavily congested rebar sections – both vertically and horizontally – were identified and installed together with any embedded elements required for the final lining together with the waterproofing system. All nozzlemen were required to demonstrate their ability to completely encapsulate the rebar and provide the requisite compaction of concrete required prior to the use of PAC being authorized for use in the permanent works. Once the mockup had been sprayed sections were cored and saw cut to demonstrate that the encapsulation had been achieved.

During production operations regular testing of the design mix was undertaken, but limited testing of the finished product were performed. The nature of the application method, plus using experienced ACI Certified nozzle men, ensures that shadowing and voids are dealt with as the shotcrete is being placed, due to the close proximity of the nozzleman with shooting from the nozzle taking place mostly from inside the reinforcement. Coring through the finished product was minimized and was typically undertaken in early applications only, using "sacrificial" additional rebar to check the encapsulation.

PAC is typically used with a waterproofing membrane which can either be a PVC or spray applied. In both cases a layer of mesh is installed approximately 1 to 2 inches away from the waterproofing and hung on the waterproofing suppliers proprietary anchor system. This mesh is spaced off the waterbarrier using bulsters to help hold the membrane back and to give the shotcrete a surface to grip against. This enables overhead applications to be undertaken with little difficulty. Where a PVC membrane system is utilized, 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 form and pour and shotcrete final linings, contact grouting is required when PAC is used to fill any voids between the waterproofing membrane and the concrete final lining. This contact grouting is not limited to roof sections only, but also a radial and more frequent distribution of grouting ports and pipes around the crown and above the spring line. This was implemented with the injection of low viscosity cementitious grouts between the final PAC lining and the membrane to ensure a tight contact between the initial and final lining.

Application examples

This method of concrete placement has been used in many different applications including a 30 inch thick 60ft SEM tunnel constructed through frozen ground (see two pictures below):

It has also been used for the creation of an inclined escalator shaft

And also used to form circular columns as part of a ventilation plenum

Client benefits

For the Client the benefits of using the PAC method are mainly associated with schedule and quality. This method is synonymous with ACI 506R-16 Guide, using an ACI Certified nozzleman in the underground which is not currently a requirement by ACI.

As no forms are used, there is no need to go through a drawn out process for their design, fabrication, delivery installation and removal. As such, the PAC method can be used throughout the duration of the project, enabling the final lining to be installed relatively quickly after excavation. This can enable follow on contracts to enter into these completed sections for access or for completion work earlier than would be the case with a form and pour lining. In addition, the lack of forms means there is no blocked access routes through the area to be lined, although the scaffolding required to install the control wires and to undertake the concrete placement may cause some blockage, it is of a far lesser duration.

The finished space is not now limited by the need to build and install forms. Continuously changing cross sections can be developed that minimize excavation, lining thickness and schedule as the PAC method can be used to match the lining to the space requirements and the challenge is now back with the designer to economize on these elements knowing that PAC is a tool in his armory.

With regard to Quality the finished product can be seen as the work progresses, there is no waiting until the form is struck to discover, voids, honeycombing etc. these are fixed as the work progresses with PAC, thereby minimizing the need to go back and undertake remedial works in completed sections of tunnel. In fact, the PAC method is often used to rectify areas where problems have been encountered with the use of formed concrete.

Summary

Form and pour concrete will continue to be the prime method of placement of final linings in underground structures. For repetitive lining operations such as lining a TBM tunnel over several thousand feet this is in reality the most practical method of concrete placement. The PAC method though offers a viable alternative placement method for use in non-uniform cross sections, shafts and other areas where the installation of a form would be problematic. It is certainly not a panacea and requires a rigorous engineered approach to the design of the structures and methods to take advantage of its flexibility and quality benefits. The challenge moving forward is to take advantage of this method to provide efficient and economic designs that take into, and accept the limitations and benefits of the PAC placement method.