
Shotcrete Lining Innovations in the United States

By Andy Thompson and Frank E. Townsend III

Historically, the permanent concrete linings for underground structures have been installed using form-and-pour methods but the use of shotcrete or sprayed concrete for the structural linings is becoming increasingly more common. Although form-and-pour methods are well proven, they do have their downsides, especially where nonuniform shapes are required.

Form-and-pour methods can be used for virtually every combination of shapes and space; however, there are drawbacks to its use, especially when nonuniform cross sections and junctions are required. Designing and installing custom-built formwork is time-consuming and, depending on the project logistics, can cause pinch points in the schedule. As clients strive to manage the scarce capital to be expended to manage existing and build new facilities, designers and constructors are increasingly being challenged to minimize the excavation and lining quantities. This brings new challenges to the use of form-and-pour 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 nonuniform openings is a well-established process, but in the last few years the boundaries of its use, especially in the United States, have been stretched. These innovations and the issues that are raised when expanding the range of shotcrete applications will be discussed in this article. Mott MacDonald, in conjunction with Superior Gunite, has been at the forefront of expanding the use of this application method in the underground environment.

FREEFORM CONCRETE

So, what are the benefits of the use of freeform concrete linings, how does it differ from shotcrete final lining (SFL), and what are the potential drawbacks?

Major capital projects in New York City, NY, have adopted the term “freeform concrete” or “pneumatically applied concrete” (PAC) to differentiate structural shotcrete placement in underground work from Metropolitan Transportation Authority’s (MTA) first “shotcrete” specification that was geared exclusively towards smoothening of underground surfaces without structural properties. Though the term “pneumatically applied concrete” has been around for over 100 years and generically includes the shotcrete process, the intent of the MTA PAC specification was to specifically include only the modern shotcrete

placement materials, equipment, and techniques required for structural liner applications. PAC uses compressed air for high-velocity placement of structural concrete to achieve full consolidation, compaction, and a uniform distribution of concrete constituents. The end product is portland cement concrete with 3/8 in. (10 mm) nominal coarse aggregate size capable of achieving conventional and high strengths, while maintaining or exceeding required end properties by design. Premixed concrete materials are pumped to the nozzle where air is added at high pressure and flow rate to achieve the required spray pattern and velocity for the concrete application.

But how is PAC different from other SFLs? A typical SFL lining uses 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 and well spaced out, as recommended by ACI 506, to minimize the opportunity for shadowing of the shotcrete around the girders and reinforcing bars. It requires a high level of application skill, workmanship, and a rigorous quality control process. It is increasingly being installed using robotic spraying, which therefore limits the finish that can be achieved to a nozzle finish. For example, a typical sequence for SFL may include: 1) installation of lattice girders at 5 ft (1.5 m) centers with a steel reinforcing bar mat placed against the waterproofing membrane at the extrados side of the girders, and partial encasement of the lattice girders; 2) shotcreting of an infill first layer between the lattice girders; 3) shotcreting of a second layer; 4) installation of reinforcing bars on the intrados side of the lining; and 5) installing a final shotcrete layer to provide minimum cover over the reinforcement. The number of shotcrete layer installations would depend on the total design thickness of the final lining. Figure 1 illustrates the installation of SFL.

PAC by contrast is used with the same reinforcing bar design used for a form-and-pour lining; thus, no specific design changes are needed to accommodate its use. It can be used around extremely heavy and congested reinforcement and against polyvinyl chloride (PVC) or spray-applied waterproofing membranes. Shotcrete is applied in layers that act monolithically in the completed concrete section. It can be hand finished to achieve any standard of finish required, including textured architectural finishes. It does,



Fig. 1: SFL installation



Fig. 2: PAC in use

however, require proper equipment, quality materials, an experienced shotcrete contractor, highly skilled ACI-certified shotcrete nozzlemen, 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 starts and during. Figure 2 shows a PAC application.

Shotcrete excels in tunnel applications where conventional forming methods are difficult logistically and also 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. This results in no forms blocking the tunnel during concrete placement operations. Scaffolding is needed but typically there is a need for scaffolding for the reinforcement installation and in any case, scaffolding is lighter and easier to erect, dismantle, and transport than a form system. PAC can be used with or without waterproofing, be it sheet membrane or spray-applied. Enhanced quality control is required for sheet membrane systems, especially in overhead applications to ensure the membrane is tight against the substrate. Figure 3 shows an example of a PAC-lined structure.



Fig. 3: Typical example of PAC lined structure

PAC has been successfully used for caverns, wyes, cross passages, vent shafts, air plenums, inclined escalator shafts, tunnel boring machine (TBM) crossovers, and tunnel junctions, all of which are locations that render uniform linear applications vulnerable to customization requirements. In these locations PAC provides a monolithic concrete placement process 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 as shown in Fig. 4, PAC is an ideal placement method for the many and varied geometries.

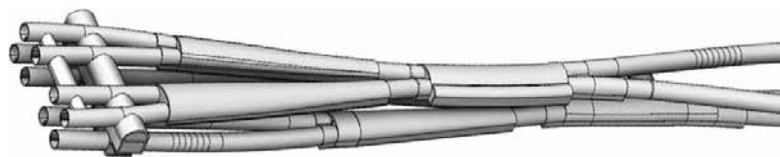


Fig. 4: Complex tunnel network lined using PAC

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 cannot equal that for a formed placement.

The use of PAC requires a rigorous quality control process. For example, when PAC was introduced to the East Side Access Project in NYC, 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 shotcrete placement for a structural component. These requirements include using a maximum No. 5 (No. 16M)



Fig. 5: Preconstruction test panels: (a) vertical; and (b) overhead



Fig. 6: Preconstruction field trial PAC mockup and hand spraying of vertical walls

reinforcing bar, a 6 in. (150 mm) minimum reinforcing bar 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 reinforcing bars can be achieved. To satisfy this requirement, the following process was put in place.

In addition to vertical and overhead compressive test panels to confirm the shotcrete mixture design, a full-size preconstruction mockup of the most complicated section of the lining was shot using the approved mixture designs and the shotcrete equipment to be used in the works. Working with the designer, the most heavily congested reinforcing bar sections both vertically and horizontally were identified and installed together with any embedded elements required for the final lining along with the waterproofing system. All shotcrete nozzle men were required to demonstrate their ability to completely encapsulate the reinforcement and embeds and provide the requisite compaction of concrete required prior to approving the use of PAC in the permanent works. Once the mockup had been shot, sections through the reinforced mockup panel were cored and saw-cut to demonstrate that the encapsulation had been achieved. Figures 5(a) and (b), 6, and 7 demonstrate this process.

Regular testing of the concrete mixture was conducted during production operations. However, limited testing of the production-place shotcrete was performed. The shotcrete process allows full visual inspection of all the concrete being placed. This helps to ensure that shadowing and voids are dealt with as the shotcrete is being placed by an experienced nozzle man. Coring through the finished product was minimized and was typically undertaken in early applications



Fig. 7: Encapsulation around reinforcement, embedments, and encasement of water barrier (on right lower side)

only, using “sacrificial” additional reinforcing bars to check the encapsulation.

PAC is typically used with a waterproofing membrane which can either be a PVC or spray-applied membrane. In both cases, a layer of mesh is installed approximately 1 to 2 in. (25 to 50 mm) away from the waterproofing and hung on the waterproofing supplier’s proprietary anchor system. This mesh gives the shotcrete a surface to grip

against enabling overhead applications to be undertaken with little difficulty. Where a PVC membrane system is used, all water barriers used as part of the waterproofing sectioning system are equipped with re-groutable hoses to ensure adequate embedment of the water barriers with the shotcrete. 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 water

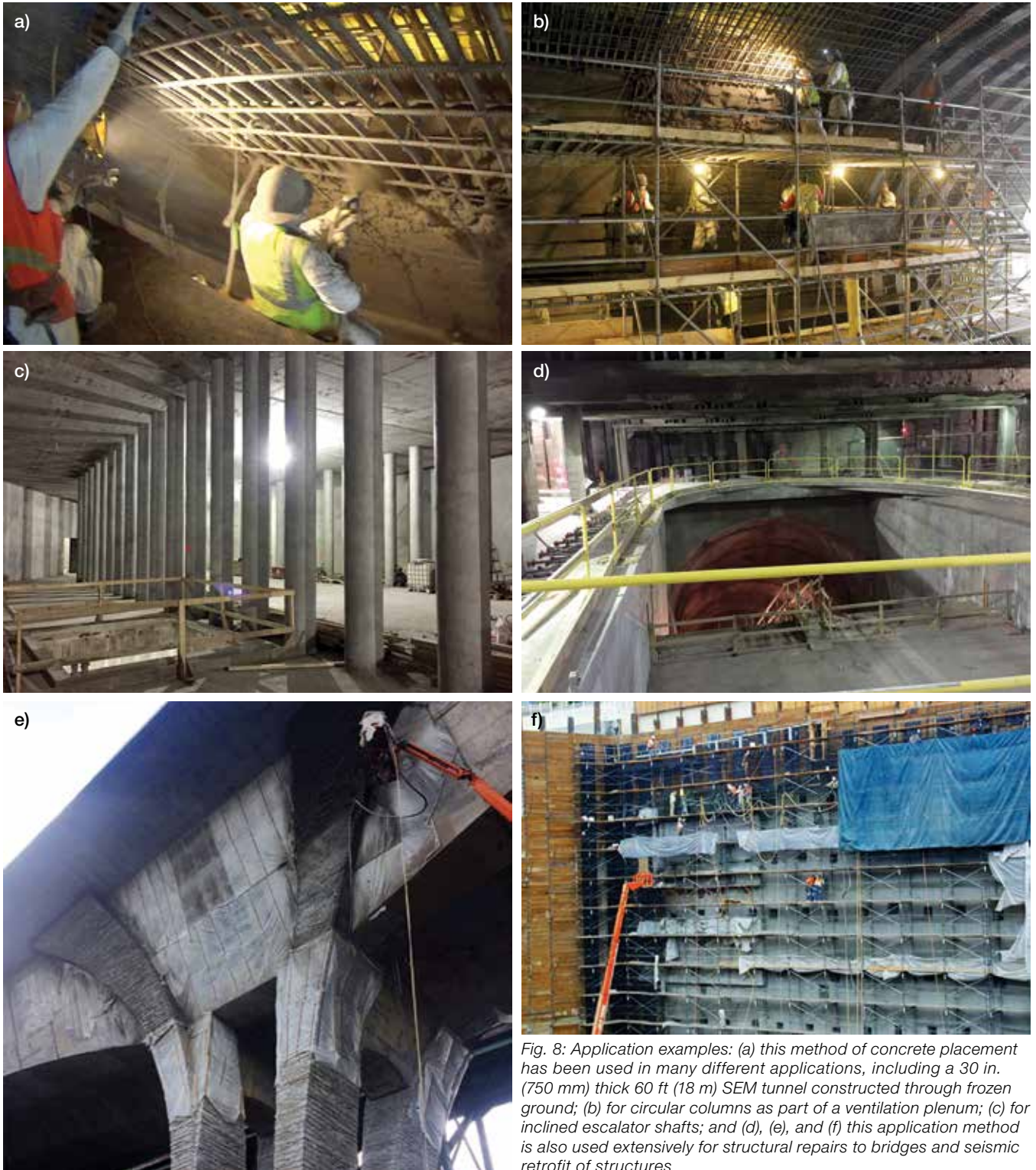


Fig. 8: Application examples: (a) this method of concrete placement has been used in many different applications, including a 30 in. (750 mm) thick 60 ft (18 m) SEM tunnel constructed through frozen ground; (b) for circular columns as part of a ventilation plenum; (c) for inclined escalator shafts; and (d), (e), and (f) this application method is also used extensively for structural repairs to bridges and seismic retrofit of structures

barrier and the PAC final lining. Similar to form-and-pour and SFLs, 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 a radial and more frequent distribution of grouting ports and pipes around the crown and above spring line was implemented with 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.

CLIENT BENEFITS

Client benefits to using the PAC method are mainly associated with schedule and quality. As no forms are required, there is no need to go through a drawn-out process of design, fabrication, delivery, installation, and removal of forms. 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, there are no forms to block access routes through the area to be lined. Scaffolding required to install the control wires and for the shotcrete placement may cause some blockage but is of a more limited 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 or her armory.

With shotcrete, the quality of the finished product is fully visible as the work progresses. There is no waiting until the form is stripped to discover poor consolidation, voids, and honeycombing. If there are isolated problems with the shotcrete placement, these are fixed as the work progresses, thus minimizing the need to go back and undertake remedial works in completed sections of tunnel and thus freeing up the completed structure earlier. In fact, shotcrete is often used to rectify areas where problems have been encountered with the use of formed concrete.

CONCLUSIONS

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 offers a viable alternative placement method for nonuniform cross sections, shaft, 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 PAC method to provide efficient and economic designs that can account for the benefits and constraints of the shotcrete placement method.



Andy Thompson has worked for Mott MacDonald since 1988 and is currently involved with the management of the design phase for the Purple Line in Maryland and the Thimble Shoal Tunnel Project in Chesapeake Bay. Between 2008 to March 2016, he worked on the East Side Access Project in midtown Manhattan serving as Program Executive, responsible for delivering around \$5.5 billion of heavy civil and underground elements of the project beneath Grand Central Terminal and Sunnyside Yard in Queens. Previously, Thompson has worked on landmark projects such as Channel Tunnel and the A20 Round Hill Tunnels in the United Kingdom, the Great Belt in Denmark, as well as other underground projects such as Harbor Area Treatment Scheme Stage 1 in Hong Kong, Greater Istanbul Water Supply Project, and Atlanta West CSO project.



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