PAC in use.

US innovation in shotcrete lining

Creating a permanent structural lining using shotcrete is not new, but recently in the USA the boundaries of its use have been stretched, as this report on its expansion in the underground environment explains.

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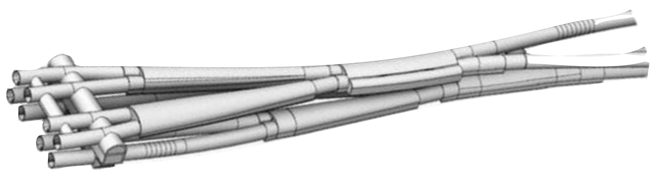
Cast-in-situ is the conventional method of installing permanent concrete linings for underground structures, but shotcrete is being increasingly used in the USA, particularly where non-uniform shapes are required. Using shotcrete for freeform concrete linings has several advantages over shotcrete final lining (SFL).

Freeform concrete – more commonly known as pneumatically applied concrete (PAC) – involves the application of structural concrete using compressed air to achieve the required consolidation and compaction, as well as the uniform distribution of cement, aggregate and water. Wet materials are pumped to the nozzle, where air is added at high pressure to achieve the correct spray pattern and velocity.

By contrast, SFL typically involves supporting steel reinforcement with lattice girders to help control the profile/geometry of the tunnel cross-section. Layers of concrete are built up to the correct thickness. Assuming the design is in line with American Concrete Institute guidelines (ACI 506[1]), the maximum bar size is #5. This requires a minimum reinforcement bar space of 12 inches (304mm) to minimise shadowing. Applying SFL correctly requires a high degree of skill and rigorous quality control, so robotic spraying is increasingly being adopted, although this restricts the finish to what the nozzle can produce. It will also likely be applied in a multi-layered process, with the number of shotcrete layers dictated by design thickness of the final lining.

Conversely, PAC adopts the same reinforcement bar design as an equivalent cast-in-situ lining. It can be used around heavy and congested reinforcement, and against PVC or spray-applied waterproofing membranes. It is applied in layers and can be completed by hand to achieve the required finish. Like SFL, PAC requires highly skilled nozzle operators as well as support crews to ensure a safe and high-quality finish is achieved. The quality-control process before and during the PAC application must be of a high standard.



Complex tunnel network lined using PAC.

A typical PAC-lined structure.

Encapsulation around reinforcement and embedments, and encasement of water barriers.

Advantage PAC?

PAC excels where forms would be difficult and/or costly to construct. There is no need to engineer, fabricate, install and remove forms in a restricted underground space, which can help ensure the tunnel is free of blockages during concrete placement. PAC can be used with or without waterproofing, whether the water resistance is a sheet membrane or spray-applied system. The quality of sheet membrane systems must be carefully monitored, especially in overhead applications, to ensure the membrane is tight against the substrate.

PAC has been used successfully for caverns, cross passages, vertical shafts, inclined escalator shafts, TBM crossovers and tunnel junctions. In these locations, PAC enables a monolithic placement process to be followed. At the same time, it provides enough flexibility for the designer and contractor to meet design and construction goals that would not be achievable with a form system.

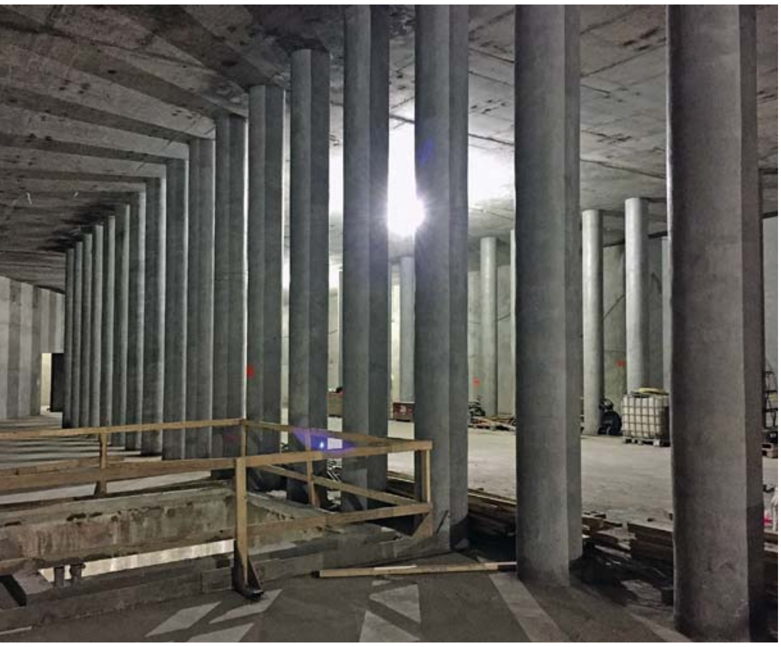
PAC is an ideal method for the multiple geometries, such as complex underground systems. However, for repetitive uniform lining operations a traditional form-and-pour approach is preferable because PAC's rate of placement is slower.

As noted earlier, a rigorous quality-control process must accompany PAC. This is to ensure that it is installed in a safe manner and complies with local and international building Standards for the use of shotcrete as a structural component.

The New York State Building Code (NYSBC) and the International Building Code (IBC) both stipulate a #5 reinforcement bar maximum and 6-inch (152mm) minimum bar spacing. These codes also prohibit the use of full-contact lap splices.

However, there is a waiver provision in the NYSBC and these requirements will not apply if the designer is satisfied that full encapsulation of the designed reinforcement can be achieved.

Using PAC for different applications – 30-inch-thick (762mm), 60ft-wide (18m) sequential excavation method (SEM) tunnel constructed through frozen ground.



Circular columns as part of a ventilation plenum.

Putting PAC to the test

To demonstrate full encapsulation is achievable using the approved mix designs and equipment, a full-size preconstruction mock-up is developed for each project. The most heavily congested reinforcement bar sections, both vertically and horizontally, are identified and installed, together with any embedded elements and the waterproofing system. All nozzle operators have to demonstrate their ability to completely encapsulate the reinforcement before PAC can be authorised for use for the permanent works. After spraying, sections are cored and sawn to show encapsulation has been achieved.

Due to the proximity of the nozzle operators to the placement location, application can be monitored to ensure shadowing and voids are dealt with when they arise. Coring through the finished product is typically undertaken only in early applications, using sacrificial additional reinforcement bar to check encapsulation.

Structural repairs to bridges and seismic retrofit of structures.

Where PAC is used with a waterproofing membrane, a layer of fabric is typically installed approximately 1–2 inches (25–50mm) away and hung on the waterproofing anchor system. The fabric gives the shotcrete a surface to adhere to, enabling overhead applications to be undertaken. For a PVC membrane system, the barriers creating the waterproofing system are all equipped with regroutable hoses. After the concrete lining has gained its 28-day compressive strength, grout is injected through the hoses to fill any voids between the water barrier and the lining.

PAC is similar to cast-in-situ concrete in that contact grouting is required to fill any voids between the waterproof membrane and the final concrete lining. Contact grouting is not limited to roof sections. The injection of low-viscosity cementitious grouts between the final PAC lining and the membrane can be used in other areas to ensure a tight contact between the initial and final lining.

A viable alternative

PAC is unlikely to replace cast-in-situ concrete as the primary method of placement of final linings in underground structures, but it does offer a viable alternative placement method for use in non-uniform cross-sections, shaft and junctions, for example. It requires a rigorous engineered approach to the design of the structures and methods to take advantage of its flexibility. The challenge moving forward is to further develop PAC to provide efficient and economic designs that account for the limitations and benefits of the method. ■

Reference:
1. AMERICAN CONCRETE INSTITUTE, 506R-16. *Guide to Shotcrete*. ACI, Farmington Hills, MI, USA, 2016.

Top: Building basement walls. Above: Incline escalator shafts.