

Shotcrete for tunnel final linings – design and construction considerations

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ABSTRACT: The use of shotcrete for tunnel final linings has gained increased popularity on a national and international basis. The high quality of the shotcrete material, flexibility in application and workability, as well as the ability to adapt to complex tunnel geometries have contributed to this popularity. When evaluating if shotcrete should be utilized as the final tunnel lining, several aspects should be carefully evaluated to determine the final product's quality and durability, as well as cost and construction schedule implications for a given tunnel configuration. Among others, geometric complexity, tunnel length and size, staging of a multi-layered application, finish requirements and type of waterproofing will play a major role in the decision. This paper establishes and discusses aspects and criteria that should be considered in the evaluation process for, or against, a tunnel final shotcrete lining. This discussion is supported using recent case histories, in particular the Pedestrian Walkback Tunnel at Washington Dulles International Airport in Dulles, Virginia, and the Weehawken Tunnels in New Jersey for New Jersey Transit to demonstrate the decision process.

1 SHOTCRETE

As reported in many documents, the material shotcrete has undergone significant developments during the past decade. Improvements of the material as well as the application method have been achieved. Intensive research in the material quality led to a better understanding of the interaction between the various constituents of a shotcrete mix, to the development of a series of new admixtures and better quality control of cement types. In particular, the use of wet mix techniques, the development of new low/non alkali accelerators, water content reducing admixtures and continuous cement quality resulted in improved final shotcrete quality. But also the use of fiber reinforcement and high-end concrete pumps and guns have furthered the shotcrete quality.

The new materials have allowed better slump control, which did not only contribute to a more steady flow with the new pumps and therefore continuous shotcrete application, but much more to a more controlled and uniform compaction and, consequently, shotcrete density. The reduction of the W/C ratio, now

enabled by the use of plasticizers and partial replacement of cement, dramatically reduced the overall pore volume and, hence, improved the durability of shotcrete. With the help of the admixtures, the quantity of rebound was reduced to acceptable values, eliminating one economic disadvantage of shotcrete.

With today's shotcrete mix designs and application equipment, high final strengths of up to approximately 70 MPa (10,000 psi) are achieved in standard applications.

Together with the use of shotcrete as permanent support material, requirements for the surface quality became more demanding. The improved workability, smaller aggregate grain sizes and better hydration heat control (cracks) enabled the contractors to satisfy these requirements. Trowel finished shotcrete surfaces (Varley 1998, Eddy & Neumann 2003) or architectural ornamental finishes (Gall et al 1998) are examples for shotcrete finishes achieved on past projects.

The compressive strength of sprayed concrete is only an indirect indicator for the shotcrete durability. Durability and water tightness are intimately interconnected. Crack development and dispersion control



Figure 1. Trowel finished shotcrete lining.

and the volume limitation of the effective pores reduce the permeability of shotcrete. Values of 10^{-12} m/sec, desired minimum values for sufficiently water tight and durable concrete, are achieved or even surpassed. If concrete is exposed to groundwater and no water flow exists across the concrete section, water absorption is of greater concern than permeability. The control of the volume of permeable pores within the concrete section and limitation to a maximum value of 14 to 17%, as recommended by various documents, is achievable in standard shotcrete applications.

Fibers are not only used to better the behavior of shotcrete during fire, but also to increase the ductility of shotcrete and shrinkage crack control and dispersion.

Above improvements combined with the inherent flexibility of shotcrete application resulted in a high acceptance of shotcrete within the industry and authorities. Shotcrete can be compared to high quality cast-in-place concrete and, in some fields, even proved to have superior characteristics.

2 LINING DESIGN PHILOSOPHIES

During the history of tunnel lining designs, different lining philosophies have been developed. Dependent on the assumption, whether or not the initial lining will have sufficient quality and durability under the project specific conditions, the initial shotcrete lining has been taken into account for the long-term support, or has been considered sacrificial. In the latter, a secondary lining had to carry all expected ground and groundwater loads in the long term. The different water tightness criteria implemented at various projects under specific project conditions led to diverse waterproofing solutions, including the use of shotcrete for water tight linings, or the installation of membrane waterproofing systems sandwiched between initial and secondary lining.

In Europe, various authorities developed their preferences with respect to tunnel waterproofing systems. For example, most of the railroad and metro authorities in Germany and Austria tend to utilize shotcrete/concrete to control the desired degree of tunnel water tightness, while the road and highway authorities prefer membrane waterproofing systems. The decision whether or not to use and be able to achieve a water tight concrete/shotcrete is also driven by the project specific environmental conditions, such as hydrostatic pressure conditions, chemical attack potential of the groundwater, and construction complexity.

In some projects, the shotcrete initial lining has been considered sufficiently durable to withstand the long-term loads over the design life. The designers of several access shafts and stub tunnels for the upgrade project of London Electricity's power supply network (London, UK) have opted to use the sprayed concrete lining, which was placed after excavation, for the long term support of these structures (Field et al 2000) as the so called Single Pass Lining. Specially detailed construction joints and high quality shotcrete were required to meet the client's water tightness criteria. Damp patches were acceptable. The lining design thickness was considered appropriate to provide sufficient long-term stability, even when a certain portion of the shotcrete lining exposed to ground and groundwater will degrade.

Similar to the classical two-pass lining systems with water tight cast-in-place concrete secondary linings, sprayed concrete has been used in lieu of cast-in-place concrete. At the Jubilee Line Extension, Contract C104 – London Bridge Station (London, UK), the complex geometry and alignment of the ventilation tunnels and the step-plate-junction housing a track bifurcation instigated the contractor to install a shotcrete lining on the inside of the initial lining (Varley 1998). The design was based on the assumption that the initial lining would deteriorate over the years and would lose its support capacity. The secondary lining has to carry all ground and hydrostatic loads expected to act during the design life. The water tightness criteria, where damp patches were permitted, were met by a high quality, steel fiber reinforced shotcrete and specially designed construction joints. A finishing layer of plain, small size aggregate shotcrete was applied to cover the steel fiber reinforced shotcrete. To meet the smoothness criteria for the ventilation tunnels, the finishing layer received a trowel finish. Similar principles have been applied at the ventilation chambers for DART's City Place Station Project in Dallas, TX (Ugarte et al 1996).

An early application of composite shotcrete linings was the lining system installed at the Heathrow Airport Transfer Baggage System Tunnel (Arnold & Neumann 1995). The shotcrete initial tunnel support was designed to provide the long-term ground support, while a

secondary layer will provide support to the hydrostatic loads. Both shells are interlocked by a rough, prepared joint surface and cross reinforcement and are expected to act as a composite structure with load sharing between the shells, effectively forming a single shell lining. Water tightness criteria, a dry tunnel had to be supplied, were achieved by high quality shotcrete and the continuous secondary layer of approx. 100 mm (4 in) thickness.

Requirements for the composite function of the shotcrete layers and the shotcrete product itself have been identified by, among others, Kusterle & Lukas (1990) and Kupfer (1990).

The more traditional two-pass lining system, combined with a membrane waterproofing system, is currently being applied at the Russia Wharf Segment in Boston, MA for MBTA's Silverline Extension (Zachary 2003). There, the initial shotcrete lining is expected to deteriorate over time under the onerous environmental project conditions. A secondary shotcrete lining is being installed to provide long-term support to full overburden ground loads, surcharge and hydrostatic loads. A full-round membrane waterproofing system completely wraps the twin tunnels to provide a dry tunnel environment and to protect the secondary lining from potentially adverse groundwater affects. High quality shotcrete is used for the long-term support. Similar principles have been applied at WMATA's Contract B10, Washington, DC for the construction of the double cross over and ventilation chambers in the mid 1980's.

Detailed design and practical considerations are described below based on a similar application at the Pedestrian Walkback Tunnel (PWT) at Washington Dulles International Airport (Hirsch et al 2003) and the Weehawken Tunnel project, in Weehawken, New Jersey (Ott & Jacobs 2003). These also include aspects of a layered shotcrete lining application. The PWT is approximately 240 m (800 ft.) long with a springline diameter of ca. 12 m (42 ft.) and features a double lining system, whereas a continuous PVC waterproofing membrane separates the initial and final linings. The Weehawken Tunnel involves the re-construction (enlargement) of a 1,269 m (4,156 ft) long, existing railroad tunnel into a two-track light rail tunnel with an underground station and a large passenger access and ventilation shaft. The widening of the tunnel to the station structure comprises a widening from an 8.4 m (28 ft) wide tunnel to an 18 m (60 ft) wide station tunnel structure to both sides of the future center platform station. Based on a Value Engineering Change Proposal submitted by the contractor, this transition, designed in a step plate junction configuration per contract, will be carried out using shotcrete for the arch final lining in a bifurcation as shown in plan in Figure 2.

Another concept of lining design is currently being applied at the King's Cross Station Redevelopment

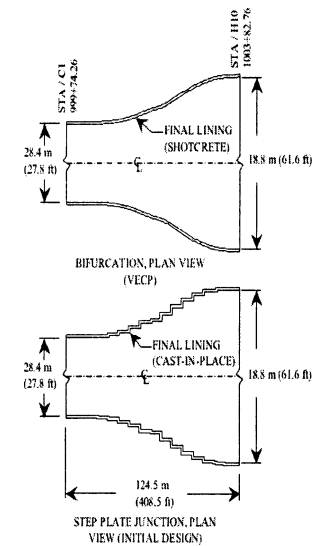


Figure 2. Concrete vs. Final shotcrete lining geometry in plan and longitudinal section (schematic).

Project, London, UK (Cox et al 2003). The complex geometrical and alignment conditions, as well as the multiple tunnel junctions and intersections proved cast-in-place concrete secondary lining an uneconomical solution. Hence, the lining system will comprise a steel fiber reinforced shotcrete initial lining, a full round membrane waterproofing system (for completely dry tunnels) and a steel fiber reinforced shotcrete secondary lining. Rebar or welded wire fabric reinforcement may be required around tunnel junctions. Due to the rather benign environment offered by the surrounding London Clay and the groundwater contained in it, it has been decided to take some benefit from the initial shotcrete lining for the long-term support. The initial lining is not expected to completely deteriorate and lose its support capabilities. This is made possible in part by new shotcrete technologies, producing high-density shotcrete, steel fiber reinforcement and a better understanding of the ground and groundwater impact on sprayed concrete.

Part of the initial lining is expected to deteriorate over time, while the remaining portion will contribute to the ground support in conjunction with the secondary lining. Due to a requirement by the owner, all steel reinforcement forming parts of the permanent tunnel support must be located inside the membrane waterproofing system. Therefore, no benefit can be taken from any steel reinforcement located within the initial lining. The initial lining is taken into account as mass concrete material that will contribute to the support in confinement. The shotcrete secondary lining will, protected by the waterproofing system, provide the long

term support for the hydrostatic loads and the remaining part of ground and surcharge loads. The waterproofing membrane, sandwiched between the initial and secondary lining, is expected to permit radial load transfer only with negligible shear transfer between the linings.

3 GENERAL APPLICATION CRITERIA

Shotcrete final linings are typically utilized where one or more of the following conditions are encountered:

- The tunnels are relatively short in length and the cross section is relatively large and therefore investment in formwork is not warranted, i.e. tunnels of less than 150–250 m (400–600 ft) in length and larger than about 8–12 m (25–35 ft) in springline diameter.
- The access is difficult and staging of formwork installation and concrete delivery is problematic.
- The tunnel geometry is complex and customized formwork would be required. Tunnel intersections, as well as bifurcations qualify in this area. Bifurcations are associated with tunnel widenings and would otherwise be constructed in the form of a step plate junction configuration and increase cost of excavated material (see Figure 2).

If the above conditions characterize a tunnel structure then a shotcrete final lining is likely to provide for flexibility in production, schedule advantages, savings in formwork and possibly savings in excavation. Therefore, a detailed shotcrete final lining cost analysis is warranted.

4 FINAL LINING EQUIVALENCY CONSIDERATIONS

4.1 Structural calculations

Structural calculations for final shotcrete linings follow the same principles and are based on the same structural codes as concrete linings. With current high shotcrete product quality and knowledge of application procedures, shotcrete is internationally viewed as concrete applied by different placement means. Due to the application process however, the reinforcement may, and in most cases will, be different in a shotcrete application. Whereas in a regular concrete section two layers of rebars at a wide spacing are sufficient, the shotcrete section will utilize welded wire fabric for better embedment within the shotcrete and to facilitate the shotcrete application. Where the loading conditions for the lining are well established, the same loadings are used in a structural calculation to arrive at reinforcement needs. Alternatively, equivalency considerations

may be applied, equating the given concrete section and its reinforcement to a proposed new section with a different reinforcement arrangement. The PWT shotcrete final lining reinforcement needs were a result of equivalency considerations, i.e. the reinforced shotcrete lining had to provide the same capacity as the cast-in-place concrete lining. An exception was the complex three-dimensional section between the mechanical room tunnel and the main tunnel where additional reinforcement beams were installed at the intersection along the groin lines (Figure 4).

When considering the application of a final shotcrete lining, the following aspects should be addressed prior to acceptance and execution in the field.

4.2 Multi-layered vs. Monolithic

In principle, there is no structural difference between a sprayed or cast-in-place concrete lining. However, when the sprayed lining is applied in multiple layers with distinct time intervals, which include installation of reinforcing steel, the bond between the different layers has to be adequate to qualify as a monolithic member in the structural sense. Limitations and requirements are therefore imposed on application sequencing, curing techniques, cleaning of surfaces and adapted concrete technology (Hoehn 1999). Keeping the time lag between shotcrete applications short aids this process. For verification, minimum tensile and shear strengths between the layers (in the joint) shall therefore be achieved.

For example and to assess the requirements for these values at the PWT project, finite element calculations were carried out that considered a representative three-layer composite system with two joint surfaces in the final lining section (see Figure 3). The model investigated the capacity of the 30 cm (12 inch) layered shotcrete final lining for the long-term condition, when the initial support is assumed to be deteriorated and overburden and live loads are imposed onto the final shotcrete lining. From this model, minimum tensile and shear strength requirements in the joints were derived to be 0.69 MPa (100 psi) and 1.38 MPa (200 psi) respectively. Hoehn, 1999 for example calls for minimum values for strength for both tension and shear of 1.5 MPa (217.5 psi). Kusterle and Lukas, 1990 rather report ranges of values to account for statistical characteristics of sampling and testing.

A review of these ranges, combined with the fact that the literature reports 1.5 MPa for tensile strength as a “universal number” and the availability of detailed calculations led to the conclusion that the above minimum values for tensile and shear were plausible.

4.3 Testing

Testing requirements for a final lining shotcrete resemble very much those of an initial shotcrete lining,

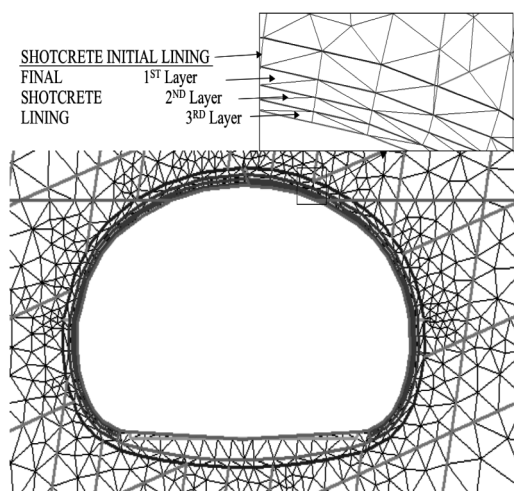


Figure 3. FE model of shotcrete lining layers.

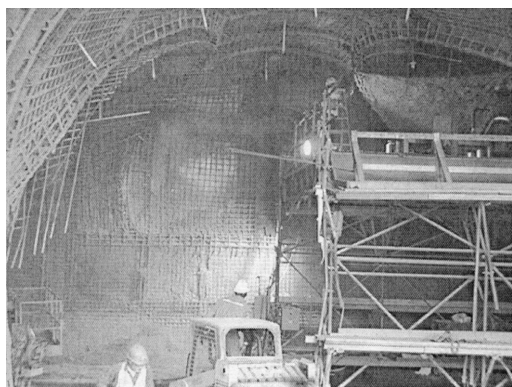


Figure 4. Shotcrete final lining installation at PWT intersection.

however with modified requirements, in particular to test for the bond capacity of the layered shotcrete. The shotcrete mix design is often developed based on historical data available from the initial lining application. At the PWT project pre- and during production testing requirements involved testing of tensile and direct shear tests on samples taken from test panels sprayed according to application and curing conditions resembling the site application, considering that the full thickness of the final shotcrete lining was to be achieved in panels not to exceed 10 m (30 ft) in length. Tensile strength was tested according to ACI 506R, whereas the shear tests were carried out according to Michigan DOT's shear test. Minimum test requirements were as per the above, 0.69 MPa (100 psi) for tensile and 1.38 MPa (200 psi) for shear

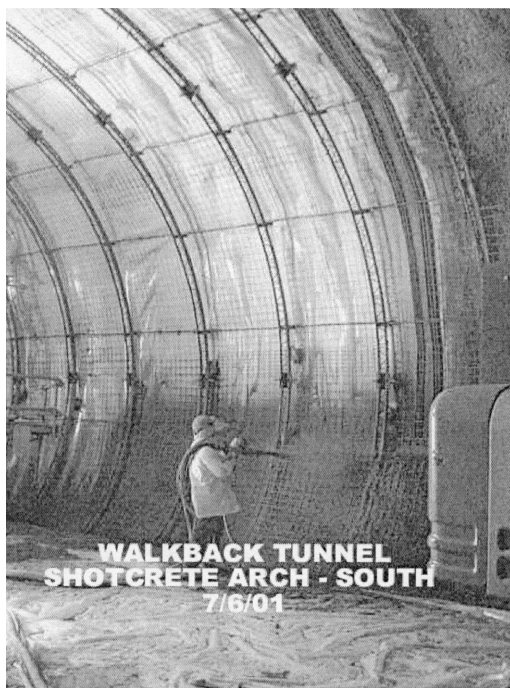


Figure 5. Final lining shotcrete application at PWT.

strength. During pre-construction, testing time intervals between applications of 24-hours and 72-hours were tried and led to strength developments yielding a minimum of 2 MPa (290 psi) in tensile strength and 4.70 MPa (680 psi) in shear after ten days. During construction, a total of four tests with two samples each were required for the entire tunnel, again time lag and application to simulate application and site conditions. The minimum tensile strength developed at three days was recorded as 0.8 MPa (116 psi), with an average of 1.47 MPa (213 psi). The minimum shear strength at three days was 5.03 MPa (730 psi), with an average of 6.83 MPa (990 psi). Therefore, test results showed that the minimum bonding requirements of the composite final shotcrete layer were well achieved by the selected construction process. Application of the shotcrete final lining is shown in Figure 5.

4.4 Waterproofing and contact grouting

The use of a dedicated waterproofing layer between the initial and final shotcrete linings creates a de-bonding effect. The degree of de-bonding depends on the type of waterproofing selected. In particular when using a loosely laid, continuous, flexible membrane type waterproofing (PVC) for complete water tightness (Gall 2000), special attention has to be given to membrane attachment, reinforcement installation and

to contact grouting. A frequent use of attachment disks will achieve a tighter fit of the membrane to the initial shotcrete lining and reduce the amount of void space otherwise created by sagging membrane sections. For the spraying of shotcrete against the membrane, a carrying layer of welded wire fabric will be required. Spacers may be used between the welded wire fabric and the membrane to push the membrane further against the initial shotcrete lining. Despite these measures, a void space will exist between the membrane and the initial shotcrete lining. For proper contact between the initial and final shotcrete linings, systematic contact grouting is essential. 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 lining perimeter should be considered for this purpose. By injecting low viscosity cementitious grouts between final shotcrete lining and the membrane will assure a tight contact between the initial and final lining.

Where water barriers have been utilized for the purpose of enhanced membrane repair (compartmentalization) a re-injectable grouting hose should be installed in the centerline of the barrier, between the ribs. Injection of grout through this hose will assure a tight embedment and contact between the ribs and shotcrete, and thus prevent leakage water to migrate across water barrier ribs.

4.5 Surface finish

There are various aspects of surface finish requirements that strongly depend on the tunnel's intended use. These include, but are not limited to, reflectivity (in vehicular tunnels), ease of maintenance (washable), smoothness (in ventilation tunnels), appearance (general), and frost resistance (exposure to cold climates). For all of the special applications solutions exist and include screeding and trowel finishing, use of special mix shotcrete, and very fine aggregates for the finishing layer, yielding surface finishes that, by appearance and function, very well compete with the cast-in-place concrete. However, such surface finishes are often not required and omission of special finishes provides for further economy. At the PWT, for example, an internal architectural finish will be used. Therefore only limited requirements for the surface were established for ease of maintenance and facilitate installation of embedments and a flatness/smoothness criterion, which called for a deviation of not more than 2.5 cm (1 inch) in 1.5 m (5 ft.), was established.

4.6 Fire resistance

Recent fire incidents, in particular in European tunnels, have initiated numerous investigations in adequate

fire testing and the improvement of the fire resistance of concrete and sprayed concrete. One prime element contributing to spalling and subsequent section thickness loss has been identified: The free water contained within the concrete section leads, when evaporating due to rapidly increased temperatures, to explosive spalling of the concrete. Tests have proven that the addition of microfilament fibers to the shotcrete mix significantly improves the fire resistance of shotcrete. The fibers melt under the influence of heat and provide escape channels for the vapor, allowing the pressure to dissipate (Tatnall 2002). A detailed review of fire resistance needs at the Weehawken Tunnel led to the application of 1.9 kg/m³ (3 lbs/cy) of microfilament fibers for the inner 10 cm (4 inch) of the shotcrete final lining in transition sections.

4.7 Method statement/application procedures

Probably the most important factor that will influence the quality of the shotcrete application is workmanship. While the skill of the shotcrete applying nozzlemen (by hand or robot) is at the core of this workmanship, it is important to address all aspects of the shotcreting process in a method statement. This method statement becomes the basis for the application procedures, the applicator's and the supervision's Quality Assurance/Quality Control (QA/QC) program. Minimum requirements to be addressed in the method statement are as follows:

- Execution of Work (Installation of Reinforcement, Sequence of Operations, Spray Sections, Time Lag)
- Survey Control and Survey Method
- Mix Design and Specifications
- QA/QC Procedures and Forms ("Pour Cards")
- Testing (Type and Frequency)
- Qualifications of Personnel
- Grouting Procedures

5 SUMMARY AND CONCLUSION

Based on general trends in the application of shotcrete for final linings and as demonstrated on recent case histories, it is apparent that shotcrete presents a viable alternative to traditional cast-in-place concrete. The product shotcrete fulfills cast-in-place concrete requirements, or sometimes can even surpass those. 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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