Watertight Permanent Shotcrete Linings in Tunneling and Underground Construction

by Knut F. Garshol and Lauro Lacerda

Sprayed concrete, or shotcrete, as is the accepted term in North America, has become an integral part of many traditional, nonmechanized (that is, drill and blast, roadheader) tunnel excavations. Even with the substantial increase of shotcrete use in North America over the last 10 years, there still exists great potential to save both time and money using this method to a much greater extent, provided some nontraditional solutions are employed.

Watertight Tunnels

Waterproofing of underground structures, especially tunnels, has long been a problem that has challenged even the most seasoned engineers and contractors. Even though shotcrete is successfully used in the construction of swimming pools, it falls short of providing a viable watertight system for use in tunnel linings. There are primarily two very good reasons for this:

1. Ground water ingress through the rock substrate underlying the shotcrete layer; and
2. Shotcrete and any other concrete, even with high cement content, needs more than 7 days of undisturbed hydration to create noncontinuous capillary pores.

It is reasonable to expect that water flow and migration will find its way through the shotcrete in a much shorter time than 7 days and, therefore, the channels created will become permanent water conduits. Many projects have focused on preventing shrinkage and other cracking phenomenon in the shotcrete to make it waterproof, but that alone will not change the requirement of undisturbed hydration and the resulting unavoidable leaks.

Furthermore, shotcrete has, for many years, been viewed as a low-quality concrete product with insufficient means of quality control during placement. This has been an additional argument against the use of shotcrete for combined permanent support and waterproofing in tunnels.

Traditional Solution

Traditionally, waterproof tunnel linings are composed of an initial temporary shotcrete layer followed by a polymer sheet membrane and a cast-in-place (CIP) concrete final lining. Typically, this is executed as an umbrella covering of the tunnel walls and roof that leaves the invert without membrane coverage.

Traditional sheet membranes are watertight, strong, elastic, and durable; however, as experience has often shown, they do not guarantee a truly waterproof lining. One problem in particular is that of undetected leakage spots in the membrane (for example, punch damage during subsequent reinforcement and concreting works) that are hidden behind the CIP concrete. Water is then free to migrate along both sides of the sheet membrane to the inside of the concrete lining, eventually making its way through construction joints or other paths of least resistance. Repair of this type of water ingress is very difficult due to the uncertainty in determining the exact location of the leak. It is often the case that the source of the leak may be far from where the water actually appears within the tunnel.

Another aspect of the traditional way of lining and waterproofing tunnels that has so far received very little attention is the fact that a majority of tunnels executed this way are over-supported. In this sense, a substantially reduced overall thickness of concrete materials would be sufficient for safe rock support. Of course, this was not a subject when there was no alternative lining method, but times have changed.

Shotcrete and Sprayed Membrane Basics

The perception of shotcrete as a low-quality material with difficult-to-control application has been influenced greatly by the way it is typically used. For decades, specifications have called for an initial, temporary (and low-quality) shotcrete support that is not to be considered part of the final, permanent lining. This specification, in turn, often leads to the supply of less-than-desirable shotcrete. Significant developments in both sprayed concrete technology and equipment have increased the availability and scope of application of uniform, high-quality shotcrete linings. The key to success is no longer hampered by technology. It is now a matter of proper decision-making and specification as well as control of execution. To ensure a top-quality lining, the following are recommended: a wet-mix shotcrete applied by hydraulic manipulator, the use of fiber reinforcement, an alkali-free accelerator with an accurate dosing system, and a water-cementitious material ratio less than 0.42.[1]

A spray-on waterproofing membrane must also be watertight, elastic, and durable and it must bond well to concrete. Membranes today offer bond strengths of more than 145 psi (1.0 MPa) on both sides when it has been sprayed onto a shotcrete substrate and shotcrete has been applied against the membrane creating a sandwich structure. This type of application prevents any water migration along the shotcrete/membrane interface and represents a major advantage if a weak spot should occur. The repair of a drip or damp spot can then be completed easily through simple point injection with a very small amount of grout.

One potential limitation of spray-on membranes is that the system needs adequate curing time from spray-applied paste to fully-cured membrane. This is frequently seen as a major obstacle and counter-intuitive to the ground water control problem (that is, the substrate must have no active water before the membrane can be placed). To address this concern, simple procedures are available in which local drains are installed before applying the membrane. Once the complete waterproofing structure is in place, these temporary drains can be closed via grout injection.

Permanent Shotcrete Lining

The use of shotcrete as a final and permanent tunnel lining still sparks much debate and opinions are often as varied as the projects about which they center. There is, however, one thing upon which many agree, and that is the use of high-quality concrete that will be durable over the design life of the project. As is well known, many of the properties of a finished concrete structure can be indirectly addressed through a required compressive strength value. In the case of a permanent shotcrete lining, a minimum of 5076 psi (35 MPa) at 28 days should be used as a reasonable starting point.

To ensure durability and uniform quality, the most important benchmarks for any shotcrete mixture design are:

- Minimum binder content of 675 lb/yd^3 (400 kg/m^3);
- Water-cementitious material ratio less than 0.42;
- Slump (without fibers in the mixture) at time of spraying to be between 6 and 8 in. (150 and 200 mm);
- The aforementioned combination is possible only with the proper use of chemical admixtures selected based on project-specific requirements (for example, open time);
- Use of so-called sulfate-resistant cements is not recommended. If sulfates are expected to be a problem, further reduction of the water-cement ratio has a much stronger positive effect without the problems caused by low C_3A cements. Some microsilica would also be beneficial;
- Alkali-free accelerators are highly recommended;
- Maximum aggregate particle size of 3/8 in. (10 mm) or less to ensure minimal rebound (less than 10%) and to create a surface roughness suitable for membrane application; and
- High shotcrete application velocity is desirable to ensure good compaction (that is, sufficient air pressure and good nozzle design).

Properties of Spray-On Membrane

A currently available membrane technology comes in powder form and is applied using dry-mix shotcrete equipment with water added at the nozzle. The membrane is typically applied to a concrete substrate (sprayed or cast) at a thickness of 0.12 to 0.16 in. (3.0 to 4.0 mm). It cures from a sticky paste to an elastic waterproof membrane in a matter of hours. The main technical properties are summarized in the following:

Form	Powder
Color	Light brown
Bulk density at 68 °F (20 °C)	37 lb/ft^3 ± 6 lb/ft^3 (590 g/L ± 100 g/L)
Application thickness	0.1 to 0.4 in. (3 to 10 mm)
Application temperature	41 to 104 °F (5 to 40 °C)
Failure stress (68 °F/20 °C at 28 days)	508 psi (3.5 MPa)
Failure strain (68 °F/20 °C at 28 days)	> 100%
Bond strength to concrete (28 days)	174 ± 29 psi (1.2 ± 0.2 MPa)
Shore hardness	80 ± 5
Flammability	Self-extinguishing (in accordance with DIN 4102-B2)

Use of Steel Fiber Reinforcement

Practical experience and tests have demonstrated that steel fibers may be used in both the substrate concrete and in the shotcrete without any damage to the membrane.

Membrane Durability

The durability of the membrane is oftentimes presented as a primary concern when this type of waterproofing technology is under consideration. While this attitude is common when dealing with any new technology, the basic chemistry of the waterproofing membrane has a nearly 40-year history. Experience with both polymer-modified mortars and concrete is widespread and well-documented. Currently, hundreds of tons of these specialty mortars are being used each year leading to the conclusion that there is little reason to expect any durability problems with a spray-applied waterproofing membrane in a concrete environment.

The chemical stability of the spray-applied waterproofing membrane has also been brought into question. Investigations have been conducted using a number of different chemical solvents and exposure times. The results of such tests have shown that the membrane is susceptible to compromise only when exposed for long periods of time to strong organic solvents and concentrated acids.

Comparison of Waterproofing Process Steps

In cases where the required thickness of the shotcrete lining (may be combined with systematic rock bolting) is less than 12 in. (300 mm), the use of a spray-applied membrane offers significant advantages. In the case of a drill and blast excavation with traditional lining and waterproofing, the following design approach is typical:

- The designer must allow space for the final lining concrete (12 in. [300 mm]) and add possible maximum thickness of shotcrete temporary support (10 in. [250 mm]) and the location of the blasting line is defined by this (no protruding rock inside of this line);
- Unavoidable look-out angle for blast holes and overbreak from blasting will typically create an actual rock contour on average more than 20 in. (500 mm) outside of the theoretical line; and
- The volume of concrete materials is therefore frequently more than 0.12 yd^3/ft^2 (1.0 m^3/m^2) of wall and roof in the tunnel (shotcrete, leveling shotcrete, and CIP concrete).

There are many advantages when choosing the shotcrete and spray-applied membrane solution:

- Total consumption of concrete materials can be reduced by 50 to 70% depending on the project;
- No need for expensive formwork;
- Work execution rate throughout the tunnel is substantially faster leading to lower overall project costs;
- Fewer problems with complicated and changing geometries and multi-stage face excavation;
- Elimination of problems caused by protruding rock bolts or other penetrations through the membrane; and
- Integrity of the final waterproofing system can be verified by simple visual inspection with weak spot repair often accomplished in minutes.

Table 1: Waterproofing Process Overviews

Traditional lining with sheet membrane	Shotcrete lining with spray-on membrane
Initial shotcrete support, typical 2 to 5 in. (50 to 250 mm) thickness.	Initial shotcrete support, typical 2 to 5 in. (50 to 250 mm) thickness.
Spray leveling shotcrete (drill and blast method) to fill in undulations in the substrate.	Where active water flow is present, drill drain holes and install short pipes using quick-set mortar.
Affix geo-textile fleece to the substrate to protect the sheet membrane from puncture.	Locally spray faster-setting thin-spray-on liner (TSL) where there is no need for drainage points, but still risk of water penetrating the fresh final membrane.
Install sheet membrane, welding, and controlling joints. Take special measures if rock bolts or other penetrations will be needed.	Spray-apply final membrane layer. Rate of waterproofing membrane application: 540 ft^2/hour (50 m^2/hour) manually and 2150 ft^2/hour (200 m^2/hour) using a robotic manipulator.
Place formwork in position and cast final concrete lining. Typical theoretical thickness is 12 in. (300 mm).	Spray final shotcrete lining, typically another 2 to 10 in. (50 to 250 mm) thickness and grout drainage points.

Spray-Applied Waterproofing In Action

Several recent spray-applied membrane applications can be referenced from around the world. In North America, the current use of dry powder spray-applied membranes has been limited to several wine caves in California.

Wine Caves

For several years, the California wine cave construction industry has been using dry-base spray-applied waterproofing membranes as a means of mitigating ground-water ingress during and after the construction of wine caves. Wine caves are generally small in cross section (10 ft [3 m]) and horseshoe or circular in shape. Another common challenge encountered during the construction of a wine cave is the oftentimes large and complex excavation geometries. An initial support layer of mesh and shotcrete is typically covered with spray-applied membrane and followed by a final layer of shotcrete. The overall shotcrete thickness is normally about 4 in. (100 mm).

Nordoy Subsea Road Tunnel, Faroe Islands

The Nordoy Subsea Road Tunnel reaches a maximum depth of 492 ft (150 m) below sea level, with a minimum rock cover of 131 ft (40 m) and was grouted ahead of the advancing tunnel face during excavation.[2] To prevent the formation of ice and the development of potholes caused by water dripping onto the roadway, about 250,000 ft^2 (23,000 m^2) of the tunnel roof was waterproofed with a spray-applied membrane system. The application was done by computer-controlled hydraulic manipulator, which ensured a very uniform membrane thickness of 0.16 in. (4 mm). Overall output (including drainage points, local TSL application, injection, and final inspection and weak spot repair) was over 17,000 ft^2/week (1600 m^2/week). The spray-applied liner is sandwiched between two 2 in. (50 mm) layers of shotcrete, thus incorporating the initial shotcrete lining into the final lining.

Chekka Tunnel

The Chekka Tunnel in Lebanon was constructed in 1971 and has a cast-in-place (CIP) concrete lining of about 12 in. (300 mm) thickness. Seasonal rains caused leakage through construction joints and cracks in the concrete and spray-applied membrane was chosen to solve the problem.

The 0.12 in. (3 mm) layer of membrane was spray-applied by computerized robot, producing more than 1615 ft^2/hour (150 m^2/hour). Shotcrete with

Fig. 1: Wine cave portal near owner's residence

Fig. 2: Wine cave after application of spray-on waterproofing membrane

Fig. 3: Application at intersection with robotic sprayer, Nordoy Tunnel

Fig. 4: Application near tunnel portal, Chekka Tunnel

synthetic fibers was sprayed for protection at a thickness of 1.6 in. (40 mm), followed by 0.2 to 0.4 in. (5 to 10 mm) gunite coating as a cosmetic finish.

Conclusions

The use of sprayed concrete (shotcrete) within the North American tunneling industry has been increasing in acceptance and is being used rapidly as new technologies are introduced and their benefits proven in the field. Water mitigating techniques have, up until now, been considered independent of temporary and final lining. Spray-applied waterproofing membranes can serve to close the gap between initial and final lining. This can make tunnel construction a more economical venture as the initial lining can now be considered as part of the final lining design.

Drill and blast excavation by its very nature creates overbreaks and in most cases, the total thickness of concrete materials with the traditional solution is far beyond what is needed for safe rock support. In such cases, the shotcrete solution can save 50% or more of the concrete materials otherwise used. In underground openings, especially those with complicated geometry (for example, metro stations, tunnel intersections, and variable size cross sections), the practical flexibility of final lining shotcrete with embedded spray-applied membrane will offer the most advantage.

In recent years, a series of successfully executed projects using the integrated spray-applied membrane system has confirmed its viability in a variety of applications all around the world, including hydroelectric power facilities, roads, and subways. When the fully-integrated, spray-applied waterproofing membrane system is suitable for application, the reduced construction time will generate significant project cost savings far beyond what is saved on the actual lining system itself.

References

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