Construction challenges of tunnel waterproofing using spray-applied membranes

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ABSTRACT

The use of spray-applied waterproofing membranes (SAWM) in tunnelling projects has gained popularity over the last two decades internationally and within Canada. This technique is particularly attractive for complex underground geometries. However, the substrate preparation and installation require good planning, rigorous quality control and extensive experience. The application of SAWM under wet conditions is challenging. This paper provides a review of the construction challenges of SAWM in modern sprayed concrete lined (SCL) tunnels based on the experience of the authors on recent high-profile projects in Canada, Quebec.

Construction requirements before, during and after the membrane application are discussed and different products are introduced and pros and cons of each one was elaborated. The application of an innovative drainage mesh is discussed.

1 INTRODUCTION

Waterproofing is one of the main challenges in the design, execution and later, operation and maintenance of the underground facilities. The use of spray-applied waterproofing membranes (SAWM) has gained popularity over the last two decades in modern sprayed concrete lined (SCL) tunnels around the world. The main advantage of SAWM over conventional sheet membranes is its flexibility at geometrically complex locations such as tunnel junctions. However, it is not possible to apply the SAWM effectively where there is active water ingress through the substrate. Even low rates of seepage behind the membrane during curing can disturb the concrete/membrane interface, causing a failure of the system.

Depending on the lining type (single shell, double shell or composite shell), waterproofing class required by the client, hydrological conditions of the site, water pressure and drainage methods (fully drained, partially drained or fully tank), designer should choose the appropriate membrane type (sheet or SAWM) and specify the project-specific conditions and requirements. A priori, the SAWM is not suitable for high permeable (at least at short-term) soils and/or rocks, if the water ingress is not managed in some way. The seemingly easy SAWM could be very challenging in terms of constructability, water management during construction, quality control and durability. This paper focuses particularly on these practical challenges, provides practical solutions and set some recommendations that can be used in future projects.
2 SAWM CATEGORIES

Many products have been developed for waterproofing of buildings, bridges and foundations. However, only few materials have been proved to be suitable for tunneling industries. Nowadays, there are three main categories of SAWM materials frequently used in tunneling (Su and Bloodworth, 2019):

1. Ethylene vinyl acetate (EVA) copolymer-based;
2. Methyl Methacrylate (MMA) reactive resin-based;

The main difference of these membranes is the curing process, water absorptions and sensitivity to the moisture. Non-reactive membrane materials dry by air exposure or hydration, whereas reactive systems cure by polymer reactions. Detailed information on material properties is available in manufacturers’ datasheets. In Canada, EVA-based materials with proven internationally independent test data have so far dominated the market. The experiences of authors mostly come from two EVA-based products.

3 CHALLENGES OF SAWM

3.1 Limited application on wet surfaces

The main limitation of SAWM is that they cannot be applied on very wet surfaces or running water. The SAWM suppliers mention that they could be applied on wet surfaces (not active water). However, and based on the experience of authors, even very wet surfaces (not essentially running) could damage membranes before the final cure. This is specifically true in case of EVA-based membranes possibly for two reasons: 1- the water absorption is very high for these materials. 2- These products are cured by a drying process

3.2 Minimum requirements

ITAtech (2013) specified a minimum bond strength of 0.5 MPa on both sides of the membrane (membrane to substrate and membrane to inner lining in case of double-bounded membranes). Several independent test data have been performed on EVA-based membranes (Su and Thomas, 2015; Su and Bloodworth, 2016; MacDonald, 2019), which proves the bond of these membrane on both sides. Based on these independent test data, products have an adhesive bond strength of around 1 MPa to 1.4 MPa and a shear strength of above 2 MPa. These tests have been done under normal atmospheric moisture conditions.

For a project at Montreal, fifteen (15) pull-off tests were performed according to CSA A23.2–6B (2019) Procedure B. For this purpose, the same sequences of real works were reproduced, i.e the primary steel fibre reinforced shotcrete (SFRS) layer was first sprayed to approximately half of the boxes depth and then finished with a 35 mm smooth layer. The two coats of EVA-based membrane (two layers of 1.5 mm) were sprayed afterwards and finally the secondary SFRS lining was added. The tests were performed after 28 days. The failure mechanism of all 15 tests was between the membrane and smoothing layer and/or secondary layer (Figure 1) with the minimum, maximum and average values of 0.28 MPa, 0.91 MPa and 0.62 MPa respectively.

The dominant failure mechanism (at the membrane and smoothing layer) as well as the results of these tests show the importance of using good material as the smooth (regulating) layer. As indicated as well by Pisova and Hilar (2017), the smoothing layer properties should be specified by designer in advance as it might significantly influence performance of the whole system (the sandwiched tunnel lining).
3.3 Adhesion of secondary (inner) lining to membrane

One of the key properties of the membrane is that the secondary lining should be able to adhere to the membrane after the membrane is cured. There are some concerns in this regard about the reactive resin-based membranes as there are no independent test data available on the bond strength of these membranes (Su and Bloodworth, 2019). This is more challenging in the case of large span tunnels where the geometry of the tunnel crown can be flatter and less of a curved arch. However, the EVA-based membranes have shown a good performance in terms of adhesion of secondary lining to the membrane.

3.4 Moisture content

The EVA and SBR membranes are heavily sensitive to the moisture contents. The polymers-based membranes absorb significant amounts of water. Based on some independent research, it was found that a wet EVA or SBR membrane has considerably lower compressive, tensile and shear stiffness and strength than a dry membrane (Thomas, 2019). It is noted that all technical data provided by manufacturers are conducted in the ambient atmospheric environment without direct contact with water. This could translate into an originally bonded membrane degrading to an unbonded state, resulting in significant change in load sharing between the primary and secondary linings.

The primary (outer) lining is more permeable than the secondary (inner) one due to the joints between each advance length, shrinkage, shadow zones and the voids left during shotcreting of the ribs or lattice girders, if any. In case of steel ribs, it is strongly recommended to leave several grouting hoses on each rib before application of first layer of shotcrete in order to inject with the ultrafine cementitious grout, acrylic or PU resins afterwards (Figure 2). The rib or lattice grouting has three benefits: 1- improve the long-term durability of the primary shotcrete by sealing the voids, cracks and fissures through the shotcrete, 2- seal the leaks and improve the impermeability of substrate and provide a more dry surface for further application of the membrane, 3- keep as much as possible the original dry mechanical properties of membrane-concrete interface.

It is strongly recommended that every composite shell lining design would specify a comprehensive grouting and drainage methodology before application of the membrane. Moreover, the designer should be cautious
about the mechanical properties provided by the suppliers as they are based on a dry condition and normally at the laboratory. Both EVA and SBR-based membranes shows a considerable reduction (35% to 40%) in mechanical properties in presence of water or moisture (Thomas, 2019).

Where the presence of water in any forms deemed to be inevitable, a conservative membrane interface design assumption (unbonded) would be more appropriate unless a very comprehensive quality control is specified by designer. Furthermore, several in-situ tests should be performed in a representative zone test prior and during construction to verify parameter values appropriate to the chosen membrane type and level of workmanship. In shallow urban tunneling, presence of the city infrastructures over the tunnel should be considered as a high potential of source of water leaks.

![Figure 2. Post grouting of ribs and/or lattice girder to minimize leakage](image)

3.5 Surface treatment

The tests results and practical case histories show that the roughness of the substrate has no direct influence on bond strength of the membrane. However, it has significant effect on the shear strength and stiffness of the membrane. The less smooth of the substrate surface, the thicker and more materials will be required to meet the specified watertightness. Achievable membrane thickness can be expected to relate to substrate roughness: where the substrate is uneven, it will be impossible to apply the consistently thin layer achievable on a smoother surface. Also, shooting the membrane onto a rough surface could create pinholes in membrane. The surface could be smooth but still uneven (undulated) which increase the material consumption. For a project, the consumption of an EVA-based membrane was increased by roughly 60% due to undulated surface even though the smooth layer had been applied. For another project, poor workmanship for smoothing layer ended up by removing the final lining to recreate the smoothing layer and start over again for the membrane and final lining. It is recommended to finish the final surface immediately after application of smoothing layer according to the supplier recommendation using broom finish and grind to remove sharp stones.

Application against a clean, regulated shotcrete surface provides a better key for the SAWM. A smoothing layer with a 4 mm maximum aggregate size is strongly recommended before membrane application, especially if the primary lining contains steel fibres.

An appropriately prepared dry surface is required prior to membrane application to achieve the required bond. According to ITAtech (2013), the substrate shall be suitably dry for the 24 hours prior to membrane application. However, and in practice, this is not straightforward as the water always tends to follow the least resistance path through the primary lining. On one project, in certain sections, after trying several days of grouting, it was observed that we were simply pushing water around the lining to new locations. Therefore, it was decided to
exclude the wet zones during application (by marking them with paint) and inject them after the membrane had cured sufficiently. The results were satisfying as, after the final grouting, the membrane had been sufficiently cured and the water could not pass the cured membrane and appear in other places. Finally, 3mm of the membrane was added manually on these places as a secondary application.

3.6 Temperature and curing time

One of the most challenging parts of every waterproofing works is the planning and scheduling of the smoothing layer, membrane layers and secondary lining. Some suppliers recommend waiting until 7 days prior to the installation of the membrane so that the main shrinkage has occurred and 85% of the final smoothing layer compressive strength is achieved. However, this delay can allow other leaks to develop, and it is preferred to apply the membrane sooner than later. Some EVA-based membranes could be applied to 24-hour old concrete.

The temperature and relative humidity (RH) of the site directly affect the curing time and consequently the logistics of the site. It is noted that all data provided by suppliers are valid for a given temperature and relative humidity. An increase in the thickness of the applied membrane also results in an increase in the required curing time.

Application of the final secondary lining (SFRC) should be optimized carefully at the site. If applied too early, it might damage the membrane and if applied too late we might have new hydrostatic pressures before complete curing, damages by dust and even other machinery at the site. Secondary lining sprayed concrete shall not be applied until the membrane has cured sufficiently to achieve an appropriate Shore A hardness. It is mentioned that the final cure of membrane would last 10 to 14 days depending on the water content and environmental conditions of the site (temperature and relative humidity). An increase in the water content during spraying results in an increase in the required curing time. Typically spray-applied membranes can only withstand active water pressure when they are completely cured and normally embedded between two concrete linings.

It is noted that if the relative humidity is 100% no evaporation can take place and the curing is stopped. For optimal curing it is recommended that relative humidity is below 90% and air speed is a minimum of 0.5 m/s to 1.0 m/s for EVA-based membranes (depending on the product), otherwise water will be retained within the membrane, although this should not impair its final impermeability. Based on our experiences, a steady temperature and humidity alongside with a permanent ventilation would accelerate the curing time and accordingly the construction.

3.7 Water inflow managements and grouting

The key challenge of waterproofing by sprayed membrane is that the surface should be sufficiently dry (at least no active water inflow) during application and during the curing time. Different methods could be used for this purpose including grouting (cementitious, polyurethane or acrylic resin), impermeable mortars applied over localized running water areas, drainage sheets and strip drains embedded in primary lining.

In drained tunnels with a permanent drainage system in the invert, both water channeling and grouting could be used before the membrane application depending on the importance of primary lining. Traditionally, geotextile drainage fleece or dimple drainage sheets have been used for water channeling. Conventional drainage mats separate the different layers of the lining (preventing any bonding) which raises the risk that water pressure can develop behind the membrane and damage the inner liner. Accordingly, leaving the voids in the lining is unavoidable. Furthermore, it is not easy to apply the shotcrete over these drainage mats and we need some mesh reinforcement to provide enough bond. When shooting nails through the fleece into the concrete substrate for fixation, the pressure from the rubber washer compresses the fleece and helps preventing water drip at the penetration. The nails should come with self-sealing rubber washers/collars whilst trying to avoid fixing nails in areas of water ingress. However, sometimes some little water leaks are observed at interface of drainage mats and these nails. A complete seal around pin penetrations is not easily achieved.
An innovative drainage mesh system could be a good alternative (Figure 3). These systems can be incorporated within the regulating layer (bonded) and can be made of HDPE, which is known for its durability. The life expectancy for certain products is estimated to 120 years compared to 50 years for conventional drainage systems.

This product was used for the first time in Canada in 2021 as part of the REM project (double arch, south section). Each panel is 800 x 1200 mm (1 m²). Each half-tube is 14 mm so it will be embedded easily in a typical smooth (regulated) layer of 30 to 40 mm. If installed continuously between primary lining and smoothing layer it could decrease the water inflow considerably. For one such product, the inner lining remains bonded to the primary lining, providing a monolithic lining (Poulsen, 2019). Each lozenge shaped gap in the mesh is about 100 x 40 mm providing a contact surface of about 70% between two consecutive shotcrete layers If the primary lining is permanent, they could be installed before the application of the primary lining (on the flashcoat).

Based on our experiences, sufficient pins should be used to fix the panel to the substrate. If not, the panels could be detached during further shotcreting. This could make the situation more complicated because all water could accumulate at one place. The panels are quite flexible so they could be bent around a corner for example, from the circumference to the headwall. Occasional and isolated water drops could be managed by grouting. However, drainage mesh systems are suitable for catching more widespread water trickling (Figure 3).

![Figure 3. Installation of an innovative drainage mesh system between the steel ribs and on the headwalls as part of the REM project (double arch, south section), Montreal, Canada](image)

4 QUALITY CONTROL

As with any material constructed in-situ, a robust and systematic quality control and a good workmanship play important roles. Preconstruction trials and use of trained operatives are vital for a successful application.

4.1 Temperature and humidity

A major factor for successful membrane performance is the environmental conditions on site at the time of application and during the curing. Temperature and relative humidity can have a significant effect on application and curing behavior. During application it is important to ensure adequate monitoring of temperature (ambient and concrete), air speed, and humidity, to ensure they remain within the recommended limits. It is also important that ventilation is working during and after application at least up to application the secondary lining.
The recommended temperature in case of EVA-polymer based membranes for at least five days after application is between +5 and +40 °C. The fluctuations of temperature during this period should not exceed 10 degrees.

4.2 Thickness control

Wet film dips (gages) and cut out test pieces of typically 50x50mm are used to check the achieved membrane thickness. ITAtech recommends minimum 10 wet film thickness measurements per each 100 m2 of the membrane.

A color contrast between two different layers would be a big asset for both spraying contractor and the quality control since areas of low thickness become obvious visually.

It is not possible to maintain a minimum 3 mm of membrane thickness everywhere. It depends on the undulation (waviness) and roughness of the substrate. It is recommended that the designer would be reasonably conservative in this regard. For example, if 3 mm is required for the project, specifying minimum 4 mm will make sure that we will have minimum 3 mm everywhere specifically in intersections and sharp transitions (areas prone to cracking). The membrane consumption could be increased considerably when the surface is not even. The thickness of the membrane can also be checked by cutting out patches at regular intervals along the length of the tunnel, and physically measuring the thickness.

4.3 Leak identification

If defects are identified prior to the application of the secondary lining, they can be repaired by additional grouting and/or by adding water sealing mortars and finally spraying additional layers of membrane. If a water leak is found after application of the secondary lining, finding the source of the leak should be easy theoretically due to the bonded nature of the SAWM (i.e., water is not able to move laterally, ITAtech, 2013).

5 DISCUSSIONS AND CONCLUSIONS

The waterproofing of underground structures by SAWM is a complex problem and achieving 100% watertightness is not an easy job. The amount of active water ingress expected should be carefully assessed before adopting a SAWM solution, as the conditions may dictate the use of systematic pre-grouting with microcemements or be more suited to a sheet membrane solution (Thomas 2019). The grouting is expensive, and the 100% efficiency of grouting is questionable unless a tight pattern is adopted at the site. The innovative drainage meshes could minimize the grouting works in partially drained tunnels, if installed properly and in a continuous manner.

The primary lining may not be as durable as the secondary lining due to the presence of shadow zones specifically at the proximity of ribs and lattice girders. If the primary lining is designed to be permanent, it is important to seal the fissures and cracks as much as possible before application of the membrane. In drained tunnels, the drainage mesh could be installed before application of permanent shotcrete (primary or secondary) to help to protect the permanent lining against long term deterioration by corrosion and freeze/thaw.

Most of the test results on membrane interface are based on the laboratory conditions and in the absence of any groundwater and moisture. Composite shell lining requires a very comprehensive quality control program. The design of SAWM should be reasonably conservative in terms of bond strength assumptions due to the limited data on long term behavior of the membranes. A safety factor of 2.0 is recommended by Thomas (2019) in this regard.

Based on our experiences, the key factors for a successful SAWM application are water management, substrate preparation, quality control, workmanship and skilled worker and respecting the minimum curing time. Using two-coat membranes simplifies greatly the quality control and thickness control at the site. The quality of the bond between concrete and membrane is the key aspect of the SAWM application. If the bond
fails, water can flow and find a way to enter the tunnel and it would not be easy to find the damaged point and to repair that. This bond could be failed by wet conditions of the substrate or by spraying the secondary lining either too early during the curing of the membrane or too late.

The results of in-situ pull off tests in dry conditions on an EVA-based membrane based on 15 tests indicated an average bond strength of 0.6 MPa which is considerably lower than the values presented by supplier (1.5 MPa). The properties reported on the product data sheets are based on laboratory testing and will vary when applied on a construction site where conditions are not similar. Environmental conditions such as temperature, humidity, dust, groundwater and/or human error in batching, water to cement ratio, consistent application thickness and adequate surface preparation are additional risks to the SAWM system.

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7 REFERENCES

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