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Waterproofing system selection for tunnel linings

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ABSTRACT: The selection of appropriate waterproofing systems for mined tunnel linings is critical to ensure the structural integrity and longevity of underground structures. This paper explores various waterproofing techniques, including sheet membrane systems, spray applied waterproofing membranes and waterproofing using admixtures, evaluating their effectiveness in different geological and environmental conditions. Key factors influencing the selection process, such as water pressure, geology as well as preparatory works and installation requirements which impact on time and cost of the project are reflected on. Implications of the choice of waterproofing systems on the design are also discussed. Published case studies of experiences with different systems are used to illustrate best practices and innovative solutions. The findings aim to guide engineers in making informed decisions to enhance the quality of installation, durability and performance of tunnel waterproofing and linings.

1 INTRODUCTION

There are several waterproofing systems for tunnel linings on the market. The traditional approach with sheet membranes is well known with respect to its limitations and advantages, but other systems have gained increasing popularity in tunnel construction due to their seemingly easier and seamless application, flexibility, and potential cost savings. However, selecting an appropriate membrane system requires a thorough understanding of material properties, in-situ conditions, and project requirements. This paper outlines considerations for a structured selection process based on key performance criteria, project-specific considerations, and industry experiences.

2 WATERPROOFING APPROACHES

Several waterproofing approaches can be applied for the waterproofing of tunnels. The selection depends on the following main factors which will be further reflected on in this paper and often not holistically considered in the decision making:

- Contractual requirements
- Geology / Ground Conditions
- Hydrogeology
- Water pressure – Drained or Tanked Tunnel
- Environmental conditions / Contamination / Ground Water chemistry
- Constructability considerations
- Other project specific requirements and considerations

2.1 *Sheet membranes*

Traditional sheet membranes as they are used for tunnel waterproofing are applied between the primary and secondary tunnel linings without bond to the secondary lining. They are often made from materials such as PVC, EPDM, HDPE or VLDPE. They can be used for drained tunnels, in the crown only, or for tanked tunnels, covering the entire tunnel circumference. The membranes often have a thin coloured protection layer on the tunnel facing side, which allows for visual identification of scratches or damage. Such membranes offer high durability and resistance to mechanical damage as well as a strong waterproofing performance under high hydrostatic pressure

These membranes are often installed against a smoothing layer. At a minimum a geotextile layer is installed as a protective layer between the concrete surface and the waterproof membrane. This acts to protect the membrane from damage from substrate roughness and acts as a water path behind the membrane. The geotextile is fixed to the underlying shotcrete lining using shot nails which also pin membrane rondels to the geotextile and are spaced at regular intervals. The sheet membrane is installed over the geotextile by welding to the membrane rondels and the separate sheets are likewise welded to together. Single or double welded seems can be carried out depending on the water pressures. Water bars welded to the membrane are used for tanked tunnels to compartmentalise the membrane, usually at joint locations. If water inflow is experienced, the leak location is most likely in the compartment where the water ingress is observed. As the membrane is not bonded to the secondary lining, without compartmentalisation, water can flow between the membrane and the lining if damage to the membrane occurs and may find a way through joints or cracks into the tunnel at a location potentially far away from the actual membrane damage.

As shotcrete does not bond to these types of membranes, its application against such membranes requires reinforcement, is time-consuming and relies on excellent quality of workmanship. Concrete linings cast with a lining formwork are commonly constructed as final tunnel linings with this type of membrane. While not always the case, often the primary lining is deemed to be temporary in this scenario. Construction joints as the weak spots in the system should membrane leakage occur, are often fitted with secondary waterproofing measures. To avoid membrane penetrations, the secondary tunnel lining should be designed to take the loads from all in-tunnel equipment to avoid the need to anchor back into the ground. To fix support bars for the installation of a reinforcement cage for the secondary lining, BA-bolts are applied.

Water ingress between the membrane and the permanent lining during construction needs to be avoided, as this water can travel in the system and find the path of least resistance into the structure. Double layer membranes for high water pressures or bonded membranes, which bond with the concrete cast against them and thus prevent a water path between membrane and lining, might be applied in special cases.

2.2 *Spray applied membranes*

Spray-applied membranes are typically used as intermediate waterproofing layers between the primary and secondary tunnel linings. The material bonds to the linings and as such forms a partially composite lining (ITAtech Activity Group, 2013). The most used materials include Ethyl Vinyl Acetate (EVA), Styrene-Butadiene Rubber (SBR), Methyl-Methacrylate (MMA), Polyurethane (PU), and Polyurea (PUA). Each of these materials has distinct performance characteristics affecting their suitability for different tunnel environments and material parameters of products differ even within the same material group (Lemke and Moran, 2015). Thus, the material selection needs to be given adequate consideration.

The installation of spray applied membranes itself is simple, they are sprayed onto the substrate like shotcrete. While there are one-pass systems on the market, often two thin membrane coats of different colours area applied, as the continuity check is for most materials except for non-conductive, resin-based membranes, purely visual. Due to the limited continuity testing options, very high-quality control during application is required. While it is often stated that due to the lack of water path between membrane and lining, the area where water is observed on the tunnel intrados is the location of membrane damage, this has not been confirmed in practical applications as the water will find the way of least resistance through the lining, which may not always be the location of membrane damage.

2.3 *Pore blocking admixtures*

Pore-blocking waterproofing technologies are hydrophilic additives that utilize a chemical reaction that creates microscopic crystals to seal pores and voids within the concrete or shotcrete matrix. These crystalline admixtures enhance the concrete's resistance to water ingress by reacting with moisture and non-hydrated cement particles to form insoluble crystals within the capillaries and microcracks. These technologies have various advantages and limitations when applied to tunnel linings (Guðmundsson,2008). Some of the benefits of these products are:

- Easily applied as they are just added to the concrete or shotcrete mix, reducing labour and construction time.
- Provide integral waterproofing and become part of the concrete, eliminating the need for external membranes and reducing installation complexity.
- They have self-healing properties as they can seal microcracks through continuous crystallization when exposed to water.
- Durable and provide long-term resistance to water.

On the other hand, they have their limitations compared to other waterproofing systems. They:

- Are not a continuous physical barrier and do not prevent water inflow into concrete but limit permeability.
- Are not immediately effective as they have a certain reaction time. Crystal growth can take days to weeks to fully block pores.
- May show varying performance depending on concrete mix design, the batching process, curing conditions, and tunnel groundwater conditions.
- They are difficult to repair if not performing to the requirements.
- May not be compatible with repair materials or prevent bonding of concrete coatings.

3 WATERPROOFING SELECTION CONSIDERATIONS

3.1 *Contractual requirements*

The starting point for the selection of any material or approach is to ensure it complies with the relevant standards, guidelines, contractual requirements and technical specifications, including the allowable inflow, wetness criteria, hydrogeological impacts, and other factors which may exclude particular solutions from the onset. The requirements will also be driven based on tunnel type and function.

3.2 *Location and environmental conditions*

The actual conditions under which the waterproofing measure is installed need to be fully understood for the design life of the tunnel. Some examples of conditions are:

- Hydrostatic Pressure: High water pressure conditions require robust and flexible membranes.
- Compatibility with groundwater chemistry is crucial. Some chemicals may degrade or weaken certain membrane types over time. Material selection may need to involve chemical resistance testing under project-specific conditions.
- Soil and Rock Conditions: Aggressive ground conditions necessitate chemically resistant materials.
- Seismic Activity: Flexible systems perform better in seismic-prone areas to accommodate ground movements. Membranes with tensile strengths exceeding 1.5 MPa and elongation capacities over 150% perform well in dynamic environments.
- Groundwater Chemistry: High salinity or acidic water necessitates chemically resistant waterproofing solutions.

– Application temperature and humidity requirements must align with site conditions. EVA-based membranes require temperatures above 5°C and humidity below 90% for optimal performance. Some membranes may not cure properly in cold or humid conditions, leading to adhesion failure. Long-term exposure to extreme temperatures including freeze-thaw cycles should be assessed.
– Curing conditions: Spray-applied membranes require a dust free environment with good ventilation.

3.3 *Hydrogeology and inflow conditions*

The hydrogeological conditions during construction and in the long term are one of the most important factors for the right choice of waterproofing system. The question if the tunnel is drained or tanked, the permeability of the ground and how much water inflow is expected during construction. For spray-applied membranes which need to be installed on a dry surface, the effort of preventing inflow during curing can potentially far outweigh any benefits. This could be grouting, water channelling, piping, strip drains on rock or installing a temporarily waterproof primer to name a few

3.4 *Installation requirements*

For sprayed membranes, a smooth surface is also important as the preparation of the substrate does affect the membrane performance (Dimmock et al., 2011) and will help to control material usage. The underlying shotcrete and substrate age is also a consideration for spray applied membrane application as the outgassing hydration heat can cause damage to the not fully cured membrane (Ballantyne, 2016). The membrane curing time needs to align with project scheduling to prevent delays. The age of the membrane at the application of the second membrane layer and the secondary lining are also to be considered for the overall construction program.

The membrane thickness criterion is to be selected carefully. Thicker membranes have better crack bridging faculties but are more prone to rupture and impact on the composite action and the design parameters (Su and Bloodworth 2016). Creep, shrinkage, temperature differences and other factors contributing to the movement of the lining needs to be evaluated. The thickness, as well as other installation factors have an impact on the design and need to be decided on early on.

Penetrations of bolts or bars through the lining can be achieved by covering the shafts of the penetrating items with membrane. Under water pressure, this measure may not be sufficient to achieve water tightness and further measures may be required (Wille and Lehr, 2005).

Comprehensive pre-production testing for spray-applied membranes under project conditions is recommended for all the above-mentioned aspects to understand the best application method for an individual project.

3.5 *Design implications*

The lining design for different waterproofing systems will fundamentally differ and this is an important understanding the operational teams do not always fully comprehend. Even without a waterproofing membrane, a permanent shotcrete lining comes with its own challenges. Delamination and even lining failure have been reported on Sydney Projects, due to loss of adhesion (Reid and Bernard 2019) or environmental conditions (Hunter 2025). While hanging linings (Barry, et al. 2021) and other mitigation measures have been proposed for redundancy and reliability (Haider, et al. 2023), shotcrete linings remain far more condition and implementation reliant than cast in-situ linings.

As a spray applied membrane bonds to the primary and secondary linings, a partial composite lining system is established and the degree of composite action which can be realised depends on the bond of the membrane to the linings. Short-term and long-term bond strength to the shotcrete linings may differ (Holter and Geving, 2016). The designer needs to undertake a sensitivity analysis, covering all conditions. The design will also need to consider any drainage system within the lining, the location of the membrane within the composite structure, the thickness of the membrane and accordant material parameters.

To avoid stress spikes and the potential of damage, it is important that the lining is constructed within the given tolerance to the required geometry (Pickett and Thomas, 2013) including waviness and ovalisation criteria, which can prove challenging to construct and can have a detrimental effect on long-term lining performance if not achieved.

3.6 *Material properties*

Any membrane material needs to meet the project requirements in view of:

- Durability and Longevity: Materials must resist aging and mechanical stress.
- Flexibility and Crack Bridging: Essential in dynamic and high-stress environments.
- Chemical Resistance: Required in aggressive underground environments.

For spray-applied membranes, different materials have different properties and as there is no clear regulation, different products within the same material group can exhibit different behaviour. Manufacture's advice and data need to be reviewed and followed, and project specific testing may be required to confirm the suitability of a material.

For sheet membranes, the material selection depends predominantly on the flexibility required as well as the hydrostatic pressure to be resisted. A very-low-density polyethylene liner material is lighter and much more flexible than a high-density polyethylene liner of the same thickness. VLDPE is stiffer and less flexible but may be more robust under high hydrostatic pressures and specific conditions.

3.7 *Testing and quality control*

Sheet membranes are welded together, and the weld seams which are inherently the weak spots can be tested via vacuum testing using a vacuum bell and pump. For this test a soap solution is spread over the seams and a vacuum bell is firmly pressed over the seam applying a vacuum. If there are any leaks in the weld, the soap solution bubbles under the vacuum. For double seams, air pressure can be applied between the two welds to test for leaks.

For spray applied membranes, in-situ testing is quite limited. The suppliers typically provide laboratory testing of the tensile strength, elongation, and chemical resistance as well as any other constraint against environmental conditions for the specific product. On-site the adhesion can be tested using a dolly and wet thickness by dipping a gauge. The dry thickness can be verified by cutting out squares from the membrane. The membrane is typically installed in two layers of 2-3 mm thickness and different colour. The two colours are used because for most materials the coverage continuity can only be tested by visual inspection. For membrane materials which are electrically conductive, continuity testing, also known as holiday testing, can be applied, which is a non-destructive method to detect pinholes and gaps in the coat. It involves using an electrical circuit, current flow is an indication of a discontinuity.

3.8 *Construction impact*

Sheet membranes require for larger tunnel sizes typically a travelling working platform or scaffold to apply the membrane. The installation is labour intensive, and the final cast in-situ concrete lining requires formwork.

A spray applied membrane in comparison is much easier and faster to apply (Saraiva et al., 2014). But the effort water management, substrate preparation and smoothing layer, sealing of penetrations, geometrical compliance of the lining in excavation and shotcrete application can take significant effort and if not carried out correctly, can lead to extensive re-work and maintenance tasks.

3.9 *Cost and life-cycle considerations*

The cost of membrane materials, installation, and potential repairs should be evaluated. This needs to be realistic and based on pre-production testing to understand all implications and what a high-quality installation takes. Furthermore, long-term maintenance and durability assessments should be included in decision-making.

A comparative analysis of initial costs vs. lifecycle costs can determine the most cost-effective option. Higher-quality membrane systems with better durability and less sensitivity to errors may justify higher initial investment by reducing long-term repair expenses. Availability and Supply Chain should be considered as readily available materials reduce lead times. Sustainable and environmentally friendly options are preferred for modern infrastructure projects. And regulatory compliance needs to be ensured as reflected on in the next section.

4 CASE STUDIES

Sheet membranes are well established and have been satisfactorily used all over the world. Membranes that have been exposed and tested after several decades of usage, e.g. by the FH Münster (Tunnel, 01/2018) show that the membranes exhibit good durability and long-term performance. Likewise, there are reports of very successful usage of spray applied membranes ((Verani and Aldrian, 2010), (Naylor et al., 2011)) but it needs to be reiterated that the application is not simple.

At the Crossrail Project in London, spray applied membranes have been employed for the tanked station structures which were fully excavated in London clay, based on the low permeability of clay and minimal expected water inflow. In some areas, where the clay interfaced with the Lambeth Group, excessive water inflow with subsequent blistering of the membrane was experienced. The spray-applied membrane in the invert was substituted with sheet membrane in these areas (Diez, 2018). This highlights the necessity to understand the conditions which may be encountered and to have planned for mitigation measures of some sort, to be able to react to the circumstances present. Some stations on the same project were waterproofed using sheet membranes whereas others utilised spray-applied membrane, depending on the ground conditions and expected inflows. A comparison of the efficiency of both approaches has been published, including the membrane application itself as well as the final lining being constructed from cast in-situ concrete in the first case versus the use of shotcrete in the latter. For the membrane application, it was found that the sheet membrane installation was faster than the sprayed membrane (Batty et al., 2016). This was due to groundwater ingress through the outer lining in areas where sprayed membrane was designated, leading to additional effort for water management and repair of damaged sections. However, in a dry tunnel the effectiveness of the spray applied membrane would have certainly outperformed the sheet membrane installation.

On some Australian projects, the experience has likewise been that the effort of cutting the correct profile, installing the lining to the correct geometry and preparing the surface for membrane installation was cost and time-wise inferior to a cast in-situ lining. It cannot be emphasised enough that the success of the application process for sprayed membranes is far more dependent on the conditions encountered the workmanship and the full comprehension of the design approach as realised by the wider industry. There is a level of risk associated with this method which does not exist in the same way for sheet membranes.

Larive et al. (2020) attempted a cost and time comparison of traditional sheet membranes and cast in-situ lining with sprayed membranes in combination with shotcrete linings. Their assessment is based on many assumptions which need to be evaluated for each individual project. Their cost analysis is based on the material costs for the membrane materials, shotcrete or concrete, formwork for the cast in-situ option and labour. Based on this assessment, under the assumed rates, they determined that for a shorter tunnel a spray applied membrane is the more cost-effective option but with increased tunnel length, the formwork cost is amortised against the higher cost of the spray applied membrane. From a program perspective, the comparison makes the spray applied membrane appearing advantageous. However, neither water management, nor surface preparation and smoothing layer works have been taken into consideration in this example.

4.1 *Project-specific selection strategy*

The following steps in addition to the inflow flowchart given in the ITA guideline or the slight alteration by (Pelz and Karlovšek 2023) is recommended to be used for selecting a tunnel membrane:

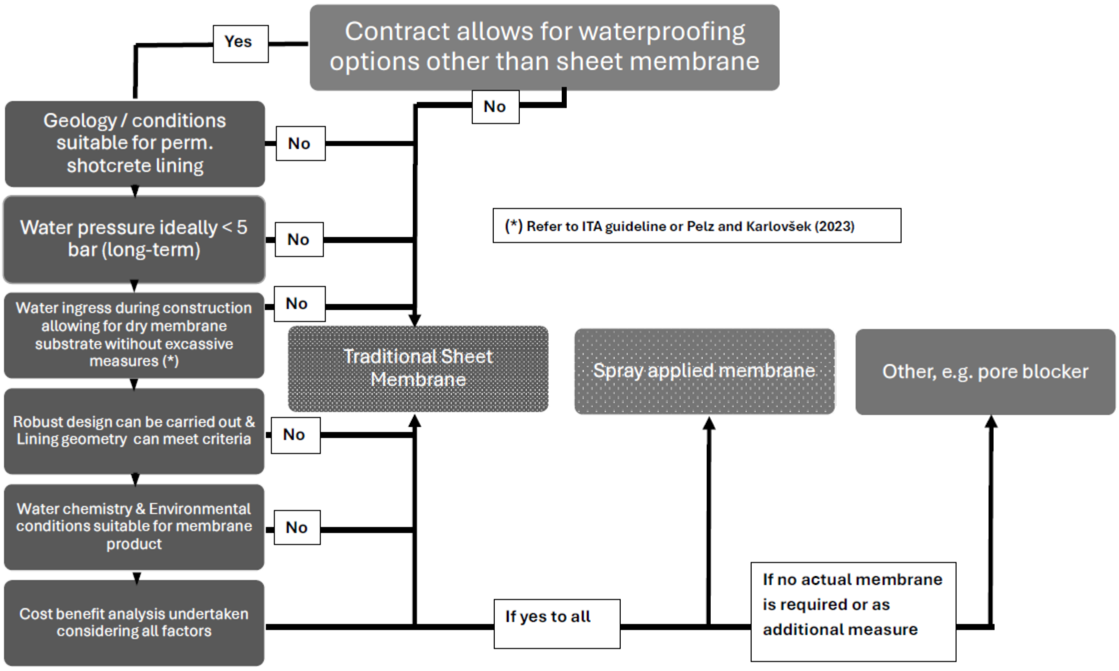

Figure 1. Membrane selection guidance

5 CONCLUSIONS

Selecting the appropriate waterproofing system for tunnel linings is a multifaceted process that requires careful consideration of various factors, including material properties, site conditions, application requirements, and industry standards. While no single system is perfect, a structured evaluation process can help project stakeholders achieve optimal waterproofing performance, cost-effectiveness, and long-term durability.

Sheet membranes, though labour-intensive, offer well-known performance outcomes, while spray-applied membranes provide faster installation but require meticulous execution and environmental considerations. Pore-blocking admixtures serve as effective supplementary solutions, particularly in environments with high hydrostatic pressure or structural movement, often in conjunction with other systems for comprehensive protection.

A comprehensive evaluation of environmental, functional, material, and economic factors is essential for making an informed choice that enhances structural integrity and ensures long-term performance. Future research should focus on long-term field performance data and the dissemination of project successes and failures to improve material selection methodologies and industry awareness.

By following these guidelines, stakeholders can minimize maintenance costs and operational disruptions, ensuring the longevity and reliability of tunnel structures.

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