Spray-applied waterproofing membranes: effective solution for safe and durable tunnel linings?

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Abstract. What is the perfect tunnel lining? Cost efficient, easy and fast to build with acceptable environmental impact? How to construct a watertight and safe tunnel lining? Would it be possible to apply a waterproofing system directly onto the rock face just after the tunnel face opening? This might be the system of the future enabling all concrete applied to the rock face to remain permanent. For now though, we would like to focus on an optimisation and examination of currently available technologies and materials, such as tunnel linings with the use of spray-applied waterproofing membranes. In this paper, the failure mechanisms of a tunnel lining with a spray-applied waterproofing membrane are described, the behaviour of spray-applied waterproofing membrane under various conditions (dry, moist, wet) is challenged and the possibilities of interface numerical modelling are presented. Tunnel lining design is mainly dependent on the geological and hydrological conditions in the considered area. The application of tunnel linings with spray-applied waterproofing membrane in both hard rock and soft ground tunnelling, are studied.

1. Introduction

To build an efficient and sustainable tunnel structure, tunnel designers must come up with a functional and reliable solution of how to fight water and deliver a safe and durable design to the client. There are various waterproofing measures such as drainage systems, plastic sheet waterproofing membranes, watertight concrete or other methods available to serve this purpose. Until now, plastic sheet waterproofing membranes have represented the most commonly used waterproofing system with all technical standards and design approaches well-known and frequently used. On the other hand, innovative solutions such as spray-applied waterproofing membranes have been introduced and heavily discussed within the profession during the last few years.

Manufacturers of spray-applied waterproofing membranes report that thanks to the use of their material, the tunnel lining can be designed thinner and so the overall cost can be reduced [1]. Material, time and cost savings are major motivations to deeply look into this problem and evaluate whether such proclamations are reasonable or if some limitations exist.

This paper is limited to the use of EVA-based (ethylene vinyl acetate) spray-applied waterproofing membranes.

2. Application of tunnel lining with spray-applied waterproofing membrane in hard rock and soft ground tunnelling

If we look at the largest projects where spray-applied waterproofing membranes have been used we can observe some similarities. No matter if the tunnels were excavated in soft ground or hard rock, the ground had to exhibit, at least from the short-term perspective, low permeability.

Since the spray-applied waterproofing membranes can be manufactured only by applying onto a surface without active water ingress, it is crucial that the primary lining remains without water ingress until the whole sandwich lining (spray-applied waterproofing membrane and secondary lining) is built. However, even if this is achieved, the question of whether the primary lining ever gets saturated or what the humidity conditions acting on the spray-applied waterproofing membrane are remains difficult to answer. A Doctoral Thesis of Karl-Gunnar Holter (Norway) shows an example of water/humidity conditions and presents real in-situ measurements of moisture conditions of the ground surrounding a tunnel lining. KG Holter states in his study [2]: “Recent reported testing of membranes for waterproof SCL (sprayed concrete lining) have not included the moisture condition and moisture properties of the constituent materials in the lining. Testing of moisture properties of membrane and concrete materials has yet to be included in guidance for design and testing of spray-applied membranes.”

To get samples from an already existing tunnel lining, test them and carry out a back analysis is possible. However, it would be almost impossible to get such data before a tunnel gets designed, respectively before a tunnel gets excavated. Prediction of real moisture conditions of a future tunnel lining is a challenge and is discussed further in chapter 4.

3. Failure mechanisms of a tunnel lining with a spray-applied waterproofing membrane

The key parameter of a tunnel lining with spray-applied waterproofing membrane is the bond between the membrane and the layers of concrete (primary and secondary lining). The tensile bond strength is not only dependent on the roughness and cleanliness of the substrate but also on the relative humidity. The values reported in various papers and manufacturer's technical sheets vary but for example ITA (International Tunnelling Association) refers to the min. value of 0,5MPa [3].

Bond is closely connected to elongation (crack-bridging capacity) of the membrane. The elongation is highly dependent on the w/c ratio and relative humidity.

Recently, it has been discovered that although contractors are advised to use a regulating layer in order to make the application of the spray-applied waterproofing membrane easier [3], the designer of the particular project should be aware of what kind of material is going to be used. Regulating layers might significantly influence performance of the whole system. If parameters of the regulating layer are not specified by the designer and contractors are allowed to choose according to their own will, the client might end up with a run-out-of-control system. The issue of regulating layer can be assumed as a good example of delicacy of the sandwich tunnel lining.

3.1. De-bonding between primary lining and spray-applied waterproofing membrane

Failure within the primary lining (or even between the primary lining and regulating layer) is not considered.

EVA-based waterproofing membranes are dissolvable in water and it is already well-known that their behaviour very much depends on the w/c ratio of the mix and their water exposure during their lifetime. Even though some researchers claim that direct contact with water is not a realistic case, since there is a high level of uncertainty such cases should be studied. Presence of water at the interface between the membrane and the primary lining might have a detrimental impact on the bond. Once the waterproofing de-bonds from the primary lining, the lining cannot be considered as a composite lining.

3.2. Failure within the spray-applied waterproofing membrane

Two types of failure can potentially occur within the membrane; mechanical or chemical failure. The mechanical failure is represented by loss of the membrane's expected mechanical properties or its rupture. The chemical stability of the membrane should be verified in terms of the chemistry of the ground water in contact with the membrane, or potential influence of other chemicals that might be added to the original mix of a spray-applied waterproofing membrane during construction.

It was reported in Tunnelling Journal this year [5] that "two colours of waterproofing are good". It is explained that it is much easier for the contractors to guarantee the right thickness and covering if two layers of the membrane with two different colours are used.

The issue might be that even if a non-harmful dye is used for colouring the membrane, it should be verified that the colour does not wash off from the membrane and does not influence its microstructure. It is important that the contractors do not make such change, such as adding a vegetable dye to the spray-applied waterproofing mix without consultation with specialists.

3.3. De-bonding between primary lining and spray-applied waterproofing membrane

The bond between the primary lining and the waterproofing membrane can be easily tested during construction by an in-situ pull-off test and the membrane can be easily repaired after by spraying or painting over the tested area.

This is not applicable to the bond between the membrane and the secondary lining though. Once the secondary lining is applied (either sprayed or cast), it is impossible to test the bond without complicated and expensive destructive tests. However, since there is no water expected to act on the interface between the membrane and the secondary lining, the risk of de-bonding of the secondary lining is much less likely than in the case of the interface between the primary lining and the membrane.

4. Behaviour of spray-applied waterproofing membranes under various conditions

As already stated, water changes the properties and behaviour of the spray-applied waterproofing membranes. It is not only necessary to provide the right water content during production of the membrane but also to evaluate and predict the relative humidity/saturation conditions in which the membrane will be placed. These conditions might change during the lifetime of the membrane (tunnel lining). The season and durability of the primary lining is an issue on its own.

It is believed that significant effects of the moisture state of the material on its physical properties are related to the nature of the material EVA polymer colloid containing many long-chain polymers, which on curing lose moisture, allowing the polymers to coagulate into a film, [6]. On exposure to liquid or vapour phase moisture, the spray-applied waterproofing membrane re-absorbs water. This appears to have an effect on physical properties of the membrane, including bond strength and elasticity. On absorption of water, the tensile strength of the membrane reduces significantly, while its elongation at break increases. Only concrete of exceptionally good quality would be expected to resist water penetration for the full tunnel service life. If the tunnel lining includes areas of 'poor' quality concrete, water penetration could occur in these areas within a matter of weeks. In reality, it is likely that the time taken for full penetration of water through the primary SCL lining will vary over a significant range, depending on the relative proportions and distribution of the varying 'quality' of concrete achieved in construction. Should significant cracking and 'honeycombing' of the concrete occur, full penetration is likely to be rapid (achieved in months/years) but, for the time being, remain localised to those areas.

Generally, it is considered likely that full saturation of the primary sprayed concrete lining will not be achieved in the lifetime of the structure. However, a test programme including curing times of each layer of the sandwich structure should be elaborated together with a schedule of design works if the design should be verified with real measured in-situ data.

5. Interface numerical modelling

All the above mentioned leads to the necessity of careful consideration of what the critical tunnel lining – interface properties – configuration is. It is expected that the shrinkage effect of the secondary lining will be increased, because the secondary lining will be restrained by the bond properties to the spray-applied waterproofing membrane, compared to a system with plastic sheet waterproofing membrane that allows for slipping interface. On figure 1, a shrinkage crack in the secondary lining can be observed.

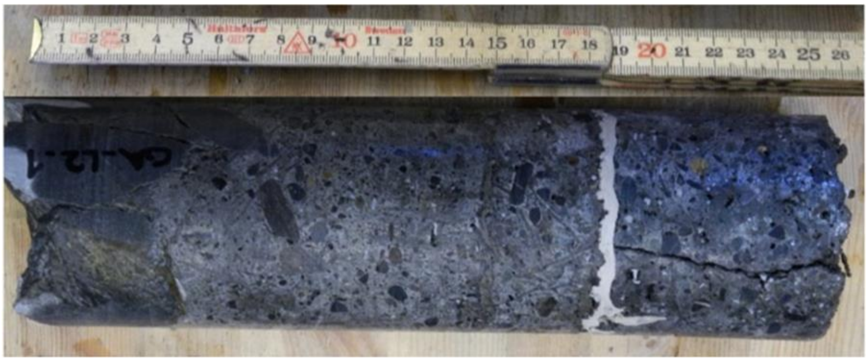

Figure 1. Shrinkage crack in secondary lining [2].

As already pointed out by Jiang Su and Michal Uhrin [6] and Pisova [7] the usual design approach taking into account compression-only action between the tunnel lining and the waterproofing membrane might not be the most conservative case and the shear and tension interface properties should be examined.

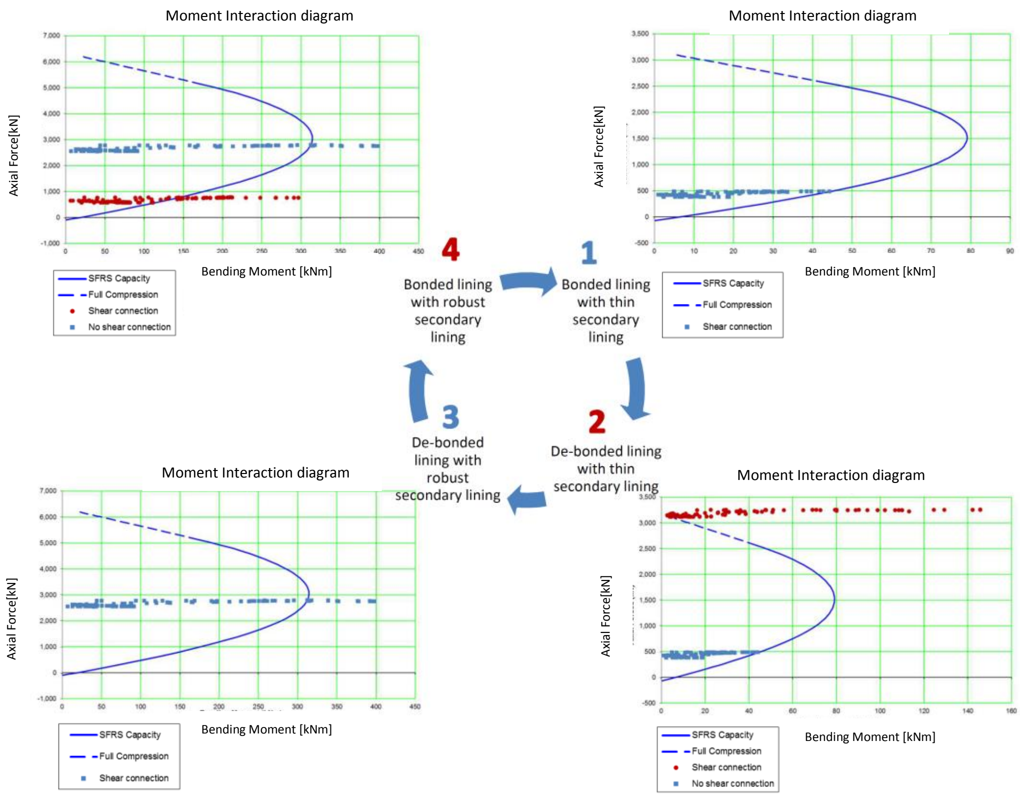

Figure 2. Numerical modelling chart.

On figure 2, design approach of a sandwich tunnel lining with the spray-applied waterproofing membrane is presented. Analysis of secondary lining with no tensile and shear bond might lead to design of a robust tunnel lining with no savings whatsoever. Also, there is a risk that even though the bond is not considered in the numerical model, it does not necessarily mean that the bond does not exist in the real structure. On the other hand, design of a thin shell secondary lining that is considered to be bonded to the primary lining through the waterproofing membrane is a risk as well, because if the secondary lining de-bonds it might not be able to carry the acting loads on its own.

6. Conclusions

The interface properties have significant impact on the load sharing between the components of the sandwich lining with spray-applied waterproofing membrane. The task for the designers is to find a way of how to define the interface properties and specify the boundary conditions with confidence. The aim is to find universal rules applicable to any ground conditions so that tunnel lining in both soft ground and hard rock can be easily designed and built. In case of the use of spray-applied waterproofing membranes, it has been proven that designers with on-site experience are much more capable to understand the delicacy and complexity of a tunnel lining with spray-applied waterproofing membranes.

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