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Interface parameters of composite sprayed concrete linings in soft ground with spray-applied waterproofing

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A B S T R A C T

The presence of a spray-applied waterproofing membrane between the primary and secondary lining layers is important to the behaviour of a composite sprayed concrete lined (SCL) tunnel in soft ground. In order to confirm the feasibility of the composite shell lining concept, the structural adequacy of the concrete-membrane interfaces under the effects experienced in a typical tunnel needs to be investigated.

This paper presents a series of laboratory tests on samples cut from composite sprayed concrete panels, to which uniaxial compression, direct tension and direct shear loadings are applied over both short- and long-term timeframes under conditions of ambient atmospheric humidity. Test results show that the interfaces are capable of resisting significant compression, tension and shear in both short- and long-term. Failures under these actions should not occur in a typical shallow SCL tunnel, and a degree of composite action between primary and secondary layers should be expected. Influence of substrate roughness and membrane thickness on the measured interface properties has been quantified. Overall, this investigation confirms the existence of composite action for composite sprayed concrete linings in soft ground, and provides parameters based on test results for further research and design.

1. Introduction

Sprayed concrete lining (SCL) is an established tunnelling method used in many countries for the creation of underground space (Kovári, 2003a, 2003b). Traditionally, SCL tunnels consist of a layer of sprayed primary lining (considered as temporary works, not part of the permanent structure), a layer of sheet waterproofing membrane and a layer of cast secondary lining, regarded as the permanent load-bearing structure (Thomas, 2009; Institution of Civil Engineers, 1996). The tunnelling industry has long expressed concern about over-excavation and material waste due to the primary lining being treated as sacrificial in the long term (Duarte et al., 2012), and there have been rapid developments in the UK over the last twenty years to tackle this issue.

One of these was the inclusion of the primary lining in the permanent structure, sometimes with addition of a second sprayed layer, but known as a *single shell lining* (Grose and Eddie, 1996; Watson et al., 1999). Although this solution was cost-effective to construct, long-term problems associated with leaks and maintenance has pushed the industry back to including a waterproofing membrane. This option, consisting of a permanent sprayed concrete primary lining, sheet or spray-applied waterproofing membrane and sprayed or cast secondary lining, but with no adhesive and shear bond assumed at the concrete-membrane interface, is called a *double shell lining*, and has been adopted for several projects such as the A3 Hindhead Tunnel (Peynolds, 2008) and Crossrail (Su and Thomas, 2014) in the UK.

Whilst efficiency gains may be achieved with double shell linings compared to sacrificial primary linings for some cases, there is a desire for further improved lining thickness efficiency by utilising the adhesive and shear bonds at the concrete-membrane interface. This option, consisting of a permanent sprayed concrete primary lining, spray-applied waterproofing membrane and sprayed or cast secondary lining, with assumption of a degree of adhesive and shear bond ("composite action") across the interfaces, is called a *composite shell lining* (Pickett and Thomas, 2011; ITAtech, 2013).

For the moment, there is still uncertainty about the properties of the concrete-membrane interface. Therefore, there is scope for further investigation into the properties of the concrete-membrane interfaces to substantiate the function of composite shell linings. A summary of the key aspects of each lining

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Table 1
Lining and interface loading scenarios for different SCL tunnel configurations.

Lining configuration	Composite action between layers	Load sharing assumptions		
		Short-term loading	Long-term consolidation loading	Long-term water pressure
Single shell lining	N/A	All on the single layer	All on the single layer	All on the single layer
Double shell lining	None	All on the primary lining	Shared between two linings	All on the secondary lining
Composite shell lining	Partial or full composite	All on the primary lining	Shared between two linings	Shared between two linings

configuration with particular regard to how short and long-term ground loading and water pressure is shared between the lining layers is given in Table 1.

Until now, only a limited number of test results on interface properties with spray-applied waterproofing membrane have been reported, most of which refer to an ethyl-vinyl-acetate (EVA) based membrane (*MasterSeal* 345) under normal atmospheric moisture conditions (Verani and Aldrian, 2010). Nakashima et al. (2015) presented flexural test results on two composite shell lining beams with and without axial force under normal ambient humidity condition. No information has been given with regards to the mechanical properties of the spray-applied waterproofing membrane interface. Field measurements by Holter and Geving (2015) on an SCL tunnel in rock with spray-applied waterproofing found the moisture content of the membrane to vary between 30% and 40%, determined by the moisture properties of the concrete and the membrane, as well as the interfaces between the two materials. Further research by Holter (2016) suggested that high moisture content in the membrane may affect its mechanical properties, *e.g.* reduce its tensile strength. In the research reported in this paper, we have also assumed the membrane to be essentially dry (*i.e.* subject only to normal atmospheric humidity) as the best estimate of conditions in typical soft ground tunnelling for two main reasons. Firstly, the very low permeability of modern sprayed concrete, and extensive grouting normally carried out to seal primary lining cracks prior to application of the membrane, would substantially slow the rate of supply of moisture to the membrane. Secondly, the hotter temperature inside the tunnel would draw moisture from membrane into the tunnel where it would evaporate into the air. In the event of a structural crack occurring in the primary lining, groundwater could contact the membrane and increase its level of saturation. However, this would be a localised effect not significant to the tunnel as a whole provided the tensile bond between the membrane and the primary lining exceeds the water pressure and thus prevents the membrane debonding from the primary lining and allowing groundwater to contact a wider area of membrane.

Confirming the feasibility of the composite shell lining concept requires a thorough understanding of the fundamental properties of the concrete-membrane interfaces under conditions representative of those in the actual tunnel and derivation of appropriate parameters for input into numerical models for design. A testing programme has been carried out with these objectives, on samples cut from composite shell test panels, including quantifying the impact of substrate roughness and membrane thickness on interface properties. This paper reports the test methods and the results obtained and their significance, referring to another EVA-based waterproofing membrane (*TamSeal 800*). This product contains more than 75% by weight of EVA co-polymer, and its functional properties are expected to be similar to other EVA-based membranes.

2. Loading conditions of the membrane interface in a composite SCL structure

Behaviour of the primary and secondary linings, in particular the distribution of bending moment and axial force, is affected not only by ground and water pressures but also the properties of the interface between the layers. As a result of the global actions on the tunnel, the interface itself may experience tension or compression, either of which may be in combination with shear, at different locations around the tunnel.

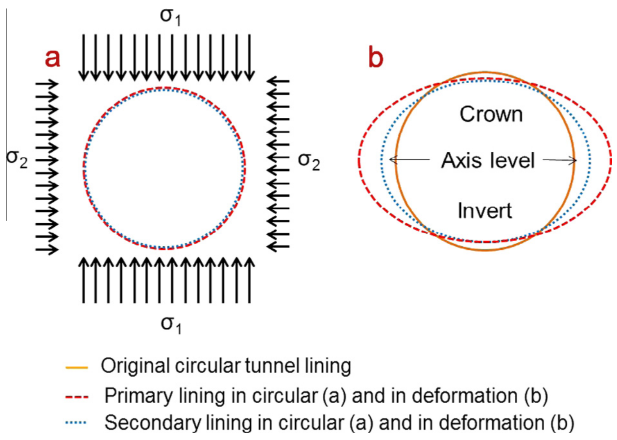

Fig. 1. (a) Idealised perfectly circular composite SCL tunnel with applied ground loading, and (b) typical resulting lining deformation.

An initial investigation into the behaviour of an idealised composite SCL tunnel under external loadings was carried out using Finite Difference software FLAC. The model consists of two circular rings in solid elements representing the primary and secondary linings, with an interface with normal stiffness of 17 GPa/m and shear stiffness of 8.7 GPa/m (Verani and Aldrian, 2010, Table 2 Specimen 0) assigned in between to represent the spray-applied membrane. Both solid and interface elements are assumed elastic. Unequal vertical and horizontal loads at a ratio of 2:1 (1000 kPa:500 kPa) were applied, as shown in Fig. 1(a), and Fig. 1 (b) shows the general form of the lining deformation that resulted.

Ovalisation of the tunnel as shown in Fig. 1(b) implies development of compressive stress in the interface between the primary and secondary linings at the crown and invert, and tensile stress at axis level. Relative shear between the lining layers will be greatest at the intermediate positions, although the maximum interface shear displacement observed was less than 1 mm. Different loading conditions (*e.g.* greater value of K_0) may change the lining deformation pattern and distribution and magnitude of interface stresses, but the interface should still experience these three stress conditions at different locations.

3. Laboratory tests and testing parameters

3.1. Laboratory tests and interface properties

In response to this fact, three types of laboratory test were conducted on samples cut from composite sprayed panels: (a) uniaxial compression, (b) direct tension, and (c) direct shear. The interface properties sought under each of these actions were peak and post-peak strengths, and short- and long-term stiffnesses. Adequate