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# Investigation of the interaction between sheet membranes, geotextile and sprayed concrete in tunnelling

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ABSTRACT: Modelling the interface connection between primary and secondary tunnel shell is an important element in the field of numerical dimensioning of tunnel linings. In this study the mechanical behaviour of the interface connection in a double shell lining (DSL) tunnel was investigated in laboratory tests. The aim of the analysis is to determine the characteristics of sheet membranes and geotextiles in case of reduced load-bearing capacity caused by degraded primary lining. For this purpose different types of tests were performed to examine the behaviour at various mechanical loads placed onto the composite system consisting of sprayed concrete, geotextile, sheet membrane and cast in place (CIP) concrete. The investigations show the influence of the surface roughness of sprayed concrete on the sheet membrane and geotextile. The results provide information on the load-sharing effects of the interaction between the primary lining and secondary lining depending on the properties of the waterproofing sheet membranes and geotextile.

## 1. INTRODUCTION

At the same time of doing long term behaviour measurements of tunnel construction material on existing tunnel tubes, sheet membranes from different sections of the tunnel, after using them up to 30 years, had been examined. The membrane located between primary and secondary lining was locally damaged. For a more exact evaluation of the reasons for the defects of the sealing detailed test set-ups were build and tests were performed.

The reasons that could lead to this undesirable behaviour of the polymer membrane can be diverse. A failure during installation of the sealing system cannot be excluded, for example damages of the membrane, which occurred while being placed on the sealing support. Another reason could be a failure of the membrane because of an unexpected system behaviour that occurred, e.g. high deformation of tunnel linings. Furthermore the materials used for the sealing system could have been wrongly chosen for the specific tunnel conditions The selected maximum grain size of the shotcrete or a wrongly applied geotextile are as well possible reasons for damages of the membrane.

The target of this research is to determine the behaviour of the sheet membranes in a compound with shotcrete and cast in place concrete in a conventional DSL tunnel construction and to analyze possible damage mechanisms. The minimum requirements of the existing guidelines for the usage of sealing for tunnel constructions will be proofed. The tests examine the guidelines and their limits and if they are sufficient to prevent damages on the sealing systems. The goal is to display the behaviour of the sealing system as close to reality as possible and to verify if the standardized tests and their requirements according to existing guidelines display it sufficiently.

Additionally the results deliver basics for numeric simulations of the sheet membranes between tunnel linings.

## 2. CONCEPT OF LABORATORY TESTS

To analyze waterproofed sheet membranes of a tunnel construction, influenced by different environmental conditions, three different test set-ups were developed and performed. The most important parameters of these trials are the different types of load conditions, which have an effect on the sheet membranes during application and during tunnel operation. Therefore the following two investigations were performed:

- tests for mechanical resistance of the sheet membranes under uniaxial load
- shear tests

The tests of mechanical resistance give information about the limits of the pressure, due to compressive stress, before damaging the membrane placed on shotcrete with different roughnesses. In this study all relevant requirements from the guidelines for sprayed concrete (ÖBV, 2009) and tunnel sealing systems are taken into account. In a further experiment the stress-strain behaviour of the sandwiched membrane layer was determined by performing shear box tests. Based on the shear tests the acting forces for the interface connection of the tunnel linings are determined for the implementation in numerical simulations. The tests were carried out with different load stages, representing the loss of load-bearing capacity of a degrading sprayed concrete lining. With consideration of these parameters in the numerical simulation shear and normal forces were developed along the interface when the initial lining deforms due to the load. These shear forces transfer additional loads to the secondary lining.

## 3. METHODOLOGIES OF LABORATORY TESTS

### *3.1 Sealing system*

The investigated sealing system (figure 1) confirms the minimum standards of the guideline Tunnelabdichtung of the Austrian Society of Construction Technology (ÖBV, 2012). The sealing system consists of the sealing support, geotextile and the polymer membrane. The thickness of the membrane is about 2.1 mm and the minimum basis weight of the geotextile is 500 g/m$^2$.

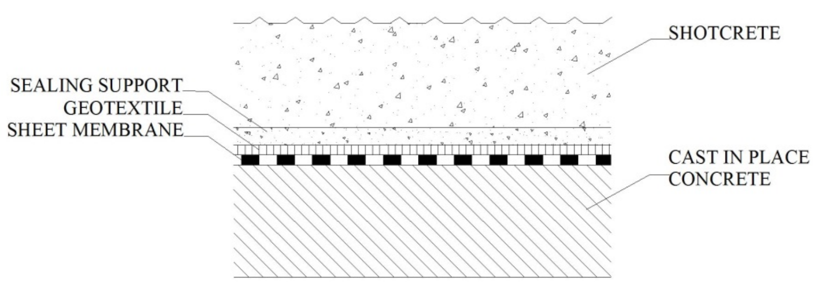


Figure 1. Sealing system

### *3.2 Sample preparation*

In order to perform the tests with real sprayed concrete surfaces, as they are found on site, all samples were taken directly at a tunnel construction site. Therefore, the same environmental and process conditions are given, which affect the surface structure. Samples with different maximum grain sizes were sprayed to investigate the impact of the roughness. One shotcrete panel was prepared with a grain size of 4 mm and another panel had a grain size of 8 mm. The sprayed shotcrete types correspond to the guideline in point 3.1. The exact descriptions and grain-size distribution are shown in figure 2.

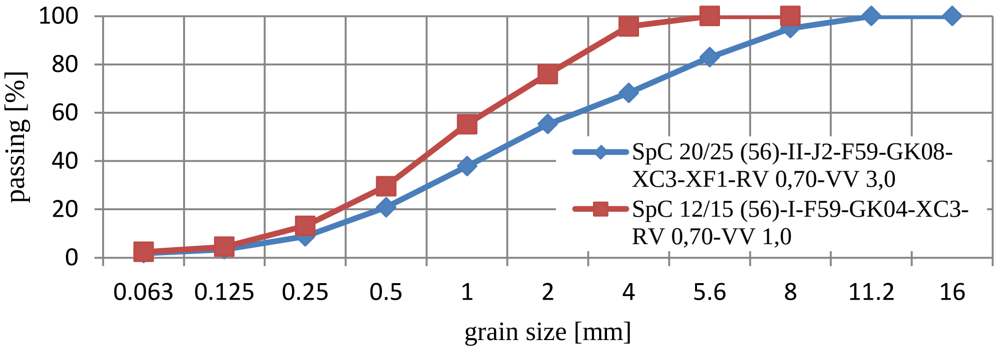


Figure 2. Grain size distribution curves

To determine the shear parameters in the shear box test, the samples for the shear test had to have a geometry with plane surfaces. In order to produce a large panel with a plane geometry for the test set-ups, the shotcrete was sprayed into a specifically build trailer (see figure 3). This way it was possible to evenly spray the shotcrete with the shotcrete robot arm. The shotcrete panels had been moved to the laboratories of the University of Leoben to post-process them. There the samples were covered with a plastic sheeting to store and prevent them from early drying.

Figure 5. Shotcrete sample

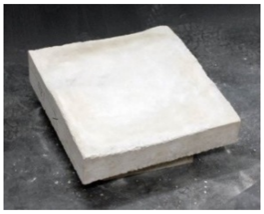

Figure 3. Shotcrete panel production on site

Figure 4. Negative mold

After the concrete had hardened for one week, the sprayed concrete panel was cut into a specific sample geometry with a diamond blade concrete cutter and driller.
In order to imitate secondary lining, which corresponds to the CIP concrete, as real as possible, a negative mold was produced under conditions, which resemble the real state secondary lining concrete when cast in the formwork carriage (figure 6). Therefore the produced shotcrete samples (figure 5) with a layer of geotextile and sheet membrane were fit into a formwork. Afterwards the wet concrete was cast into the formwork and compacted, which represents the secondary lining concrete and later cast on the negative mold. In order to simulate the set formwork pressure, the drying concrete was loaded with weights, which correspond to a formwork pressure of about 80 kN/m².

### *3.3 Determination of the roughness*

For the determination of the roughness of the surface photogrammetric pictures of the roughness profile were taken and analyzed (see figure 6). The analysis of the roughness was made in accordance to ÖNORM EN ISO 4287:2012 and ÖNORM EN ISO 4288:1998. The points on the profile line were exported in a CVS file and according to ÖNORM EN ISO 16610-21:2013 a gaussian filter was laid over the profile to determine the roughness. These analyses were performed in the program Matlab.

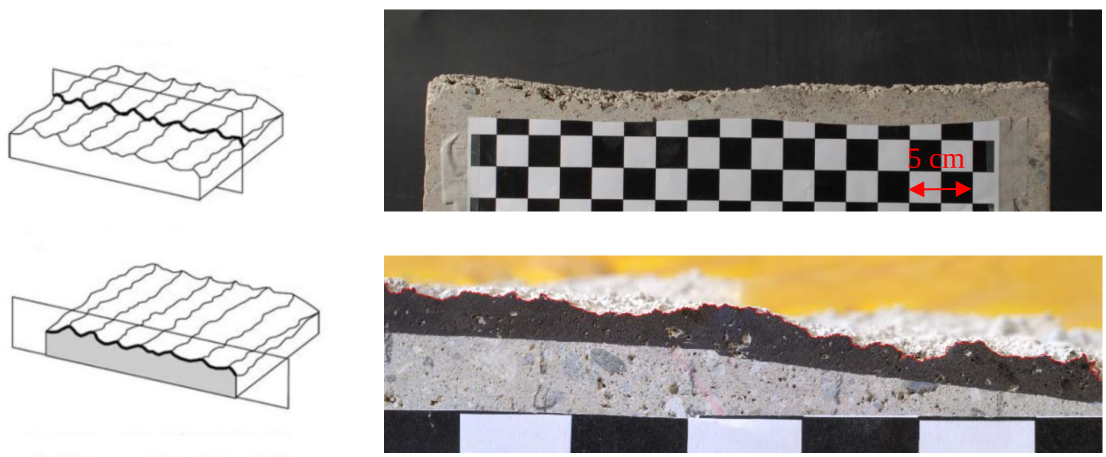


Figure 6. Roughness measurement on sample profile

### *3.4 Tests of mechanical resistance*

In order to simulate mechanical loadings of sheet membranes in tunnel constructions, tests were made in the laboratories, which analyze in detail the contact of shotcrete, sheet membranes and CIP concrete of the secondary lining. In the test the loadings, which are caused by the viscose consistence of the concrete, before the hardening process, onto the sheet membrane, are simulated. The peak of the support pressure in the tests is applied from water in a pressure vessel.

The test set-up consists of a pressure vessel with a diameter of 60 cm. There, the drilling cores of the shotcrete samples with a diameter of 250 mm were build in. The free space around the sample was filled with concrete so that a plane contact area is given. In order to remove the sample and to drain the condensed air below the sealing, recesses and a notch had been considered (figure 7 right side). On the surface of the shotcrete a geotextile and a sheet membrane was applied and clamped by a flange. The upper part of the vessel was screwed to the lower part of the vessel. After filling the equipment with water, the sheet membrane was loaded with the pressure of the water. The pressure of the water represents the formwork pressure of the concrete.


Figure 7. Test set-up

In order to reach higher pressure loads onto the membrane a second test set-up, a hydraulic testing machine, has been used. The pressure on the sheet membrane in this case is from a negative mold, as described in 3.5, and not as in the first set up by hydraulic loading. Two different load stages were used for the sample. The first one was about 2.0 MPa, which was as high as the one in the pressure vessel, and the second load stage was 5.0 MPa.

### *3.5 Shear test*

The influence of the roughness of the concrete is examined in a shear box test. Samples with dimensions of 50 x 50 cm were prepared for the shear tests. The given shear box test set-up allows to fix the sheet membrane at the rectangular shear frame. This way it is possible to guarantee that the plane the shear band is formed. The maximum of the shear displacement was with 20 mm and a constant velocity of 0.667 mm/min. For better visualization the test set-up is shown in figure 8. In order to get a reliable shear plane the tests were performed with three different normal forces or normal stresses.

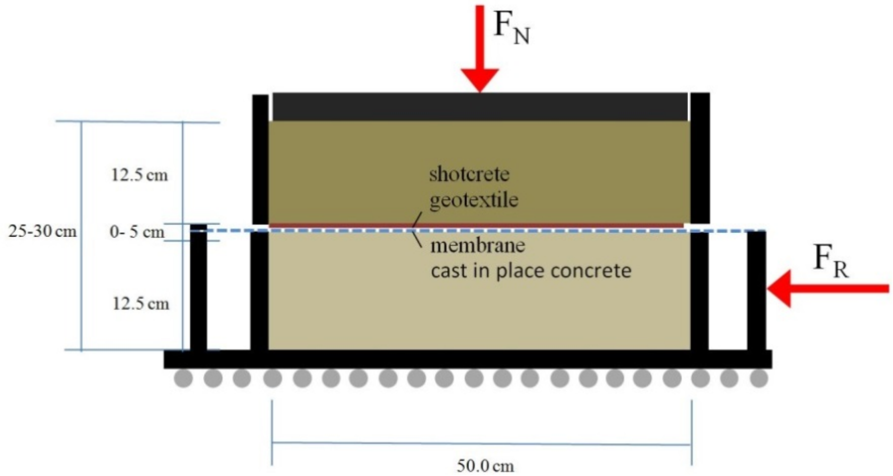


Figure 8. test set-up of the shear box test

During the shear tests the applied normal force $F_N$ and the shear force $F_R$ were measured by load cells. In the tests the maximum normal force of the shear box equipment was applied. The normal force was about 150 kN and this corresponds to a support pressure of about 0,65 MPa in a tunnel construction.

# 4. RESULTS AND DISCUSSIONS

## *4.1 Determination of the Roughness*

The results of the roughness measurement are listed in table 1 below.

Table 1. Roughness values

| Shotcrete | | Rt | Ra | Rq |
|---|---|---|---|---|
| SpC 8 mm | [m] | 0.00825 | 0.00108 | 0.00136 |
| SpC 4 mm | [m] | 0.00722 | 0.00093 | 0.00116 |

## *4.2 Tests of mechanical resistance*

The tests in the pressure vessel under uniaxial loading show that using the maximum grain size according to the guideline (ÖBV, 2012) no damage is caused at the membrane. The minimum weight of 500 g/m$^2$ for the geotextile is high enough to compensate the impact of 20 bar of water pressure. As shown in figure 9 and 10 only individual imprints are visible.

Figure 9. Membrane after test

Figure 10. Geotextile after test

But also the sheet membranes from the test with the hydraulic testing machine at 2.0 MPa and 5.0 MPa (figure 13, 14) show no damages or defective areas. It is visible that the imprints in the sheet membrane become deeper. The loading of 5.0 MPa is representative for the support pressure, which does not appear in pressure relieved tunnel constructions, because this would lead to extremely high normal forces in the tunnel lining.


Figure 11. Test set-up for the hydraulic testing machine

Figure 13. Geotextile loaded with 5.0 MPa

Figure 12. Membrane loaded with 5.0 MPa

### *4.3 Shear tests*

The results of the shear test show that the peak of the shear strength is developed at a shear displacement of 5-6 mm. In figure 14 it is shown that after reaching the peak of the shear strength an almost constant strength has been developed. Transferring the results of the shear

tests into a normal stress to shear stress diagram, a linear function is formed. As a result the Mohr-Coulomb criterion is valid and can be used for the calculation.
The resulting shear strength is comparatively unaffected of the roughness of the shotcrete, because the toothing is compensated by the geotextile layer. Only points with high roughness depths are pressed into the membrane (compare figure 15), connect the membrane with the shotcrete and therefore increase the shear strength. These individual imprints are decisive for the maximum shear strength. The connection between membrane and shotcrete would cause a shift of the relative movement from the membrane/geotextile into the membrane/secondary lining interface. In consequence of the normal and the shear stresses the sheet membranes were damaged at the imprints at the end of the shear tests.

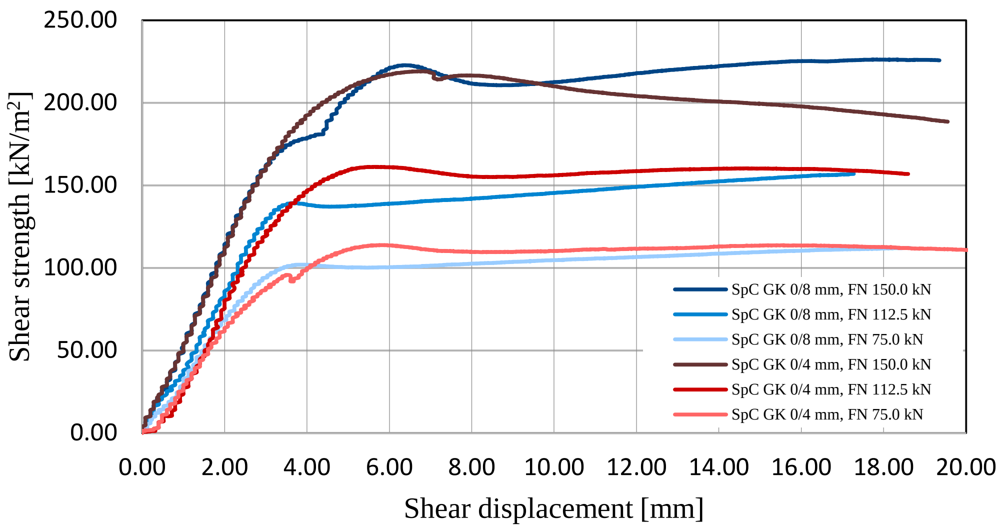


Figure 14. Shear curves

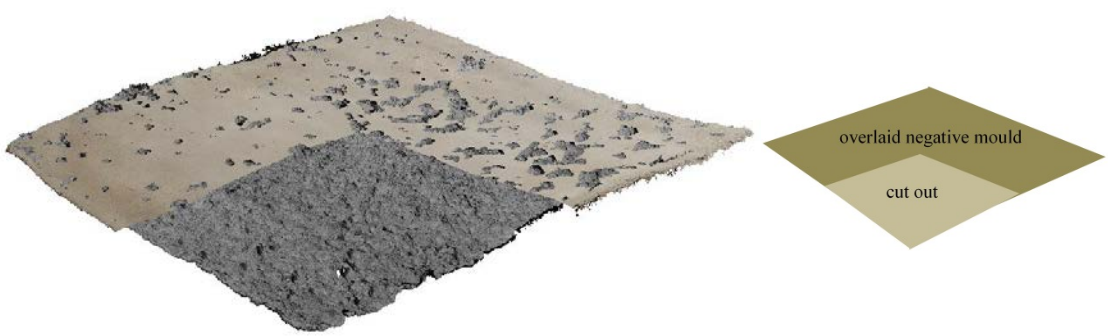


Figure 15. Three-dimensional image of the imprints

The shear strengths resulting from the tests and their determined shear parameters can be integrated in static calculation of tunnel shells. The resulting shear angle when performing with a grain size of 8 mm and a roughness given in table 1 is 16.5 degrees. Taking the parameters into account into the contact conditions of the simulation a more realistic system behaviour for the load transmission between the tunnel linings can be calculated.

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