

Performance of EVA-Based Membranes for SCL in Hard Rock

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Abstract The bonded property of multi-layered sprayed concrete tunnel linings (SCL) waterproofed with sprayed membranes means that the constituent materials will be exposed to the groundwater without any draining or mechanically separating measures. Moisture properties of the sprayed concrete and membrane materials are therefore important in order to establish the system properties of such linings. Ethyl-vinyl-acetate based sprayed membranes exhibit high water absorption potential under direct exposure to water, but are found to be significantly less hygroscopic and exhibit lower sorptivity (water absorption rate) than sprayed concrete. This material behavior explains the relatively dry in situ condition of the membrane that was observed. Measured in situ moisture content levels of the membrane material in tunnel linings have been found to vary within the range of 30–40 % of the maximum water absorption potential, and show a decreasing trend over the first 4 years after construction has been completed. A model for the mechanical loading, moisture condition and thermal exposure of the membrane and the resulting realistic parameters to be tested is presented. Laboratory testing methods for the membrane materials are evaluated considering possible loads, moisture and freezing exposure. Material testing of membrane materials was conducted with preconditioning to realistic moisture contents and under different temperature conditions including relevant freezing temperatures for tunnel linings. The main effects of the in situ moisture condition of the tested membrane materials

are favorable tensile strengths in the range of 1.1–1.5 MPa and low risk of freeze–thaw damage. The crack bridging capacity of the tested membranes is found to be sensitive to temperature. With membrane thicknesses in the range of 3–4 mm, crack bridging capacity up to 4–6 mm opening of the crack width at 23 °C and approximately 1 mm opening at –3 °C was measured for the tested membranes. No significant reduction of the tensile bond strength could be demonstrated after 35 freeze–thaw cycles with –3 °C minimum temperature at the membrane location in the lining. Further work is required to verify the performance of the SCL system under exposure to high hydrostatic pressures and the effects of long term mechanical exposure.

Keywords SCL · Sprayed concrete · Loading conditions · Sprayed waterproof membrane · EVA based membrane · Testing · Durability

Abbreviations, definitions and terms

SCL	Sprayed concrete lining. Permanent tunnel lining system based on fiber-reinforced sprayed concrete as the structural material with different possible waterproofing measures which are integrated into the sprayed concrete structure. Such linings may also include rock bolts for rock reinforcement
EVA-based sprayed waterproofing membrane	Ethyl-vinyl-acetate copolymer material used in the category of sprayed waterproofing membranes referred to in this paper

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DCS	Degree of capillary saturation (%). Degree of saturation of concrete with respect to total suction porosity, equal to the ratio of water content of a given concrete specimen to its water content at saturation at immersion at atmospheric pressure at mass equilibrium
RH	Relative air humidity (%)
COV	Coefficient of variance, ratio of standard deviation to mean value

1 Introduction

In hard rock environment in the Scandinavian countries permanent rock support linings are widely constructed with fiber-reinforced concrete and rock bolts (NGI 2013; NCA 2011; STA 2011). The final waterproofing and thermal insulation has normally been resolved by constructing a separate suspended shield structure (NPRA 2012; STA 2011). Modern requirements for service lifetime, serviceability and maintainability have raised concerns with the use of these shield lining systems. Cast-in-place concrete lining waterproofed with sheet membranes or pre-cast concrete segment linings for rail and road tunnels have therefore been proposed as the future technical solution in rail and road tunnels subjected to high traffic density (NPRA 2012; Holter et al. 2013).

SCL with sprayed ethyl-vinyl-acetate (EVA)-based membranes are being considered as a possible technical solution under certain conditions as an alternative to the well established lining systems. The main benefit would be the reduced total lining thickness since the rock support lining based on sprayed concrete can be utilized as part of the final lining, and large concrete thicknesses can be avoided. Although such linings with spray applied membrane have been constructed for approximately a decade and have seen increased use in some countries, the main properties and function have yet to be fully understood.

SCL waterproofed with a sprayed membrane represents a continuously bonded multi-layered structure from the rock mass to the tunnel lining surface. The bonded property of the lining structure implies that the constituent materials of the lining will be exposed to the groundwater without any constructed draining or mechanically dividing measures. The construction process of spray-application produces continuous and bonded interfaces, which also can be assumed to be perfect hygric contacts between the different

layers. The moisture properties of the membrane material and the concrete on either side of the membrane, as well as the exposure to any groundwater in the immediate rock mass will influence the moisture condition of the materials in the tunnel lining.

A research project in Norway has been carried out in order to assess the suitability of this lining system for modern rail and road tunnels. An important part of this research has been to conduct site and laboratory investigations in order to establish the function and properties of such linings. This work contains several main modules which have required detailed studies. The investigation of the in situ moisture condition and possible moisture transport mechanisms through sprayed concrete tunnel linings are published in Holter and Geving (2015) which forms the basis for moisture exposure during laboratory testing. The freeze–thaw resistance of the sprayed concrete in tunnel linings under realistic moisture contents and thermal exposure has also been investigated and will be published in a separate paper.

The scope of the present investigation is to study the properties of the membrane material, particularly the loading conditions for the membrane, evaluate testing methods and conduct testing of important parameters under varying climatic conditions. A conceptual model for the tunnel lining is presented in order to define the main items, its properties and the important processes for the waterproof SCL system. The in situ exposure conditions for the membrane will be substantiated from field investigations. The context which is considered in our study is a hard rock environment in which the primary rock support structure is considered stable and has no imposed ground induced loads or deformations on the bonded membrane and inner lining.

This study refers to EVA-based membranes with products from two different suppliers. The study contains the following main elements:

- Definition of material model based on the layout of the tunnel lining.
- Model for different loading scenarios of the membrane.
- Field investigations: moisture content, thermal exposure and in situ tensile bond strength.
- Evaluation of laboratory test methods for membranes in a SCL context.
- Laboratory investigations of hygroscopic properties of the concrete and membrane materials.
- Laboratory investigations of mechanical properties of the membrane material.
- Analyses of results.

The first findings of this study were presented at the World Tunnel Congress 2014 (Holter et al. 2014). Findings from additional field and laboratory investigations have been included. The recommendations of the ITAtech Design Guidance for

Sprayed Membranes (ITA/AITES 2013) compiled by Dimmock (2014) will form the basis for the evaluation of test methods for membranes. Adjustments to these test methods will be discussed and made based on the loading model and the findings from the thermal and moisture analyses.

Possible degradation processes and long term durability under relevant mechanical loading and climatic exposure, as well as recommendations regarding testing details and acceptance criteria will be discussed based on the results.

2 Conceptual Model for Tunnel

Current SCL designs and the application methodology for concrete and membrane materials form the basis for the conceptual model. The bonded and thus undrained interfaces of the multi-layered structure result in moisture transport processes governed by the hygroscopic properties of the constituent materials. For hard rock tunnels the tunnel lining structure consists of a primary lining based on fiber-reinforced sprayed concrete and rock bolts. In poor ground conditions in a hard rock environment reinforced sprayed concrete ribs are frequently used for permanent ground support (Grimstad et al. 2008; Mao et al. 2011). In order to produce a suitable substrate for the application of the membrane, a regulating layer of sprayed concrete is normally required. For these investigations the regulating layer has been applied using wet-mix fiber-reinforced sprayed concrete. Dry-mix sprayed concrete or mortar for use in the substrate for the membrane has been excluded from this investigation. The conceptual model for the waterproof SCL is shown in Table 1 and Figs. 1 and 2.

Fiber-reinforced sprayed concrete is the structural material in an SCL structure. The sprayed concrete mix

designs investigated in this study all represent state-of-the-art developments in mix designs and robotic application technology. Four different sites with different mix designs were included in this study. However, the basic mix designs differ only slightly from one another. The mix design of the sprayed concrete used for detailed material investigations in our study is shown in Table 2. The range of the contents of the different components is also given.

All together five membrane products nominated M1 to M5 have been included. For the field investigations of the lining structure only M1 has been analyzed so far.

3 Mechanical Loading, Moisture and Freezing

3.1 Mechanical Loading

3.1.1 Loads from the Rock Mass

A study of the possible loading of rock support linings based on sprayed concrete and rock bolts from the groundwater and rock mass has been undertaken (Holter 2014). The current practice with the use of rock mass classification according to the Q-system (NGI 2013) normally ensures rock stability with a high factor of safety. From this study it is concluded that in hard rock environment the stresses and loads which occur in tunnel linings are negligible in most cases. Even in severe weakness zones significant loading of the tunnel lining structure does not normally take place, other than local loads (Mao et al. 2011; Grimstad et al. 2008; compilation by Holter 2014). Still, special design of the rock support is undertaken for severe weakness zones.

Table 1 Main items in the conceptual model for waterproof SCL

Main item in conceptual model	Situation, condition	Processes
Tunnel lining structure with sprayed concrete and membrane in walls and crown	Bonded undrained contacts from rock surface through all materials	Moisture transport through lining structure
	No thermally insulating materials in lining	Differential shrinkage, of concrete on either side of membrane
	Concrete of different ages	Thermal and shrinkage induced movement of cracks in concrete
		Exposure to water at cracks
Rock mass below GW table	Saturated jointed rock material	Exposure to movement at cracks caused by gravitation, shear displacement, stress release, swelling
	Exposure to GW at the rock-concrete interface	Local saturation of concrete material at rock-concrete interface
Tunnel space	Climate in tunnel	Water flow on joints into tunnel through invert
	Seasonal variations in temperature and relative humidity	Exposure of lining surface to tunnel climate
		Heat flux from rock mass to tunnel space
		Cyclic freezing and thawing of lining
		Change of properties of membrane and concrete

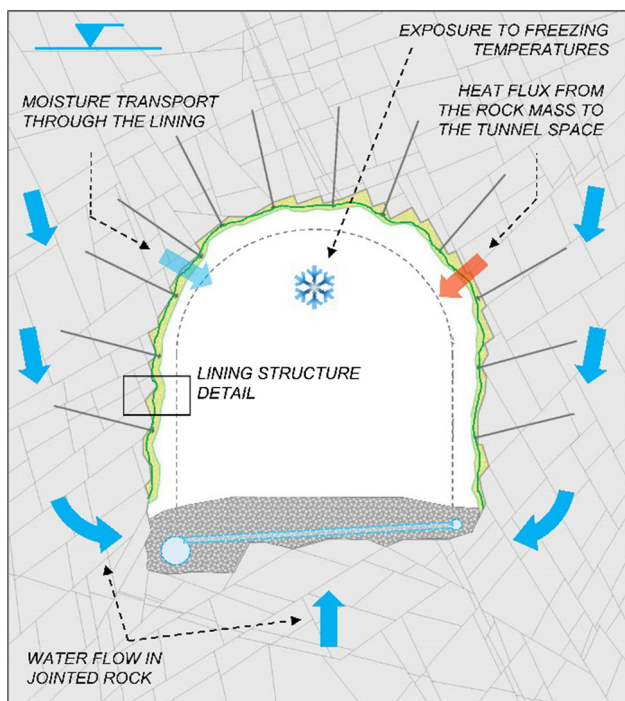


Fig. 1 Main elements in the conceptual model for a tunnel with permanent SCL based on fiber-reinforced sprayed concrete, sprayed waterproofing membrane and rock bolts constructed in hard rock. Detail is shown in Fig. 2

3.1.2 Ground Water Induced Loads

The waterproof SCL lining system represents an undrained structure. Hence, possible water pressures acting on the tunnel lining need to be considered. A study including monitoring of groundwater pressures around sprayed

concrete tunnel linings with drained invert has been conducted (Holter 2014). These results indicate water pressures lower than the hydrostatic pressure in the immediate vicinity of the tunnel lining.

Any occurrence of unfavorable ground water pressures in the immediate rock mass needs to be considered in the rock support design as well as evaluating the need for drainage measures where this is feasible. Ground water under a certain pressure can possibly saturate cracks and imperfections in the sprayed concrete in the primary lining. Under such circumstances a wet-crack situation with ground water pressure exposing the membrane locally can be hypothesized. The investigated sites in this study had a water pressure near the lining of maximum 2 bars. No deterioration of the lining structure was detected at any of the test sites. However, the wet crack problem at higher hydrostatic pressures cannot be assessed in detail from this study.

3.1.3 Loads from the Weight of the Tunnel Lining

The gravity induced stresses in the tunnel lining caused by the weight of the tunnel linings represent a constant static load. By considering a thickness of the inner layer sprayed concrete of 100 mm, and assuming that the concrete lining is “hanging” on the substrate a gravity induced tensile stress of 2 kPa in the center of the tunnel crown can be calculated.

3.1.4 Dynamic Loads from the Traffic Area of the Tunnel

Rail and road tunnels are exposed to fluctuations in air pressure caused by traffic. Highway and high speed rail

Fig. 2 Detail of waterproof SCL. Conceptual model with section of the lining structure with the constituent materials, moisture transport processes and exposure to freezing

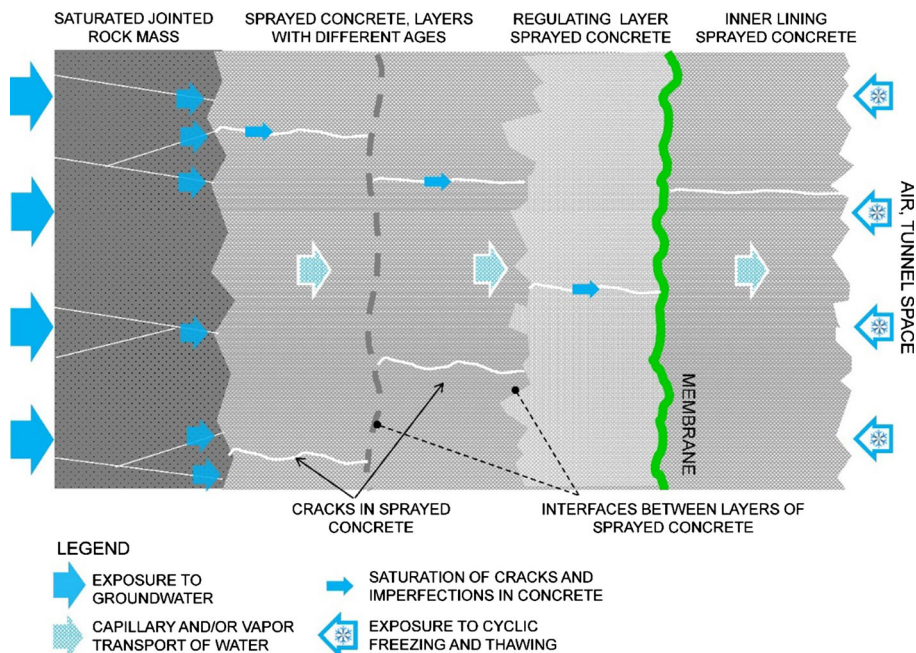


Table 2 Sprayed concrete mix design for the Harangen road tunnel, and range for other sprayed concrete mixes for tunnel sites investigated in this study

Component	Quantity	Range for investigated concrete mixes from the other test sites
Cement CEM II A-V 42.5 17–18 % fly ash content	502 kg/m ³	488–513 kg/m ³
Micro silica fume	25 kg/m ³	21–26 kg/m ³
Water added with base mix	240 kg/m ³	202–245 kg/m ³
Water added with accelerator at spraying nozzle	17 kg/m ³	17–20 kg/m ³
Water/binder-ratio ^a	0.45	0.44–0.47
Aggregate 0–8 mm	1497 kg/m ³	1497–1588 kg/m ³ , fractions used 0–4, 0–8, 0–10 mm
Superplasticizer	7 kg/m ³	7–10 kg/m ³ , different suppliers
Fiber reinforcement, structural polypropylene (PP)	9 kg/m ³	5–9 kg/m ³ (PP) 0.5–1 % by volume
	1 % by volume	40 kg/m ³ (steel) 0.6 % by volume
Binder paste content	0.43 m ³ /m ³	0.41–0.44

^a Considering equivalent binder content: weight of cement + two times weight of micro silica

tunnels in Norway have design requirements for expected maximum dynamic loads and number of loading events throughout the service lifetime. Current design requirements for rail and road tunnels (NPRA 2006; NNRA 2012; STA 2014) are shown in Table 3.

For a tensile loading consideration, the values for air pressure changes shown in Table 3 are considered changes in tensile stress. For a high speed double track rail tunnel a single design event for traffic induced air pressure change in the tunnel imposes tensile stresses with a factor five times higher than the calculated static gravity induced load from the tunnel lining. However, the dynamic air pressure induced loads are approximately a factor 100 times lower than measured in situ tensile bond strengths of the membrane-concrete interfaces. It is therefore considered very unlikely that this dynamic loading represents a dynamic fatigue scenario for a bonded SCL structure.

3.1.5 Deformations of the Membrane Over Cracks in the Concrete and Shear Deformations Along the Concrete-Membrane Interfaces

Deformations can occur in the sprayed concrete lining caused by the differential shrinkage of the concrete with different age on either side of the membrane, as well as

thermally induced contraction of the concrete material due to fluctuations in the temperature. Such deformations are illustrated in Fig. 3. Each layer of concrete will exhibit a set of shrinkage cracks which will normally not persist across layers with different age. The membrane represents a deformable and ductile material, which is designed to bridge the cracks in the concrete. The two concrete layers, one on either side of the membrane may be applied with a time gap of several weeks or up to several months. From a load consideration perspective, the full shrinkage potential from the covering layer of concrete is assumed. Shrinkage properties of sprayed concrete has been subject to a recent Swedish study (BeFo 2014; Bryne et al. 2014a). Free (unrestrained) shrinkage of fiber-reinforced sprayed concrete after approximately 120 days was found to be in the range of 0.045–0.055 %, or 0.45–0.55 mm per m on laboratory sprayed slab specimens subjected to norm climate conditions (storage at RH 50 % and 20 °C, following 7 days of initial curing under water). In a restrained context such as bonding to rock as well as the unilateral exposure to moisture on the rock side and drying on the air side, precise assessments of shrinkage are difficult to make. Effects of surface drying may cause high shrinkage locally at the concrete surface. The shrinkage will result in the cracking of the concrete material. The use of fiber

Table 3 Dynamic loads in modern tunnels given as sudden change in air pressure per design traffic event

Tunnel type	Design speed (km/h)	Air pressure change per event (kPa)	Number of events in service lifetime	Time interval between each event, range
Highway, double carriageway	140 ^a	1.5	5×10^7	20–60 s
Rail, double track	250	10	1×10^7	2–5 min
Rail, single track	250	8	1×10^7	2–5 min

^a 20 km/h higher than legal speed limit

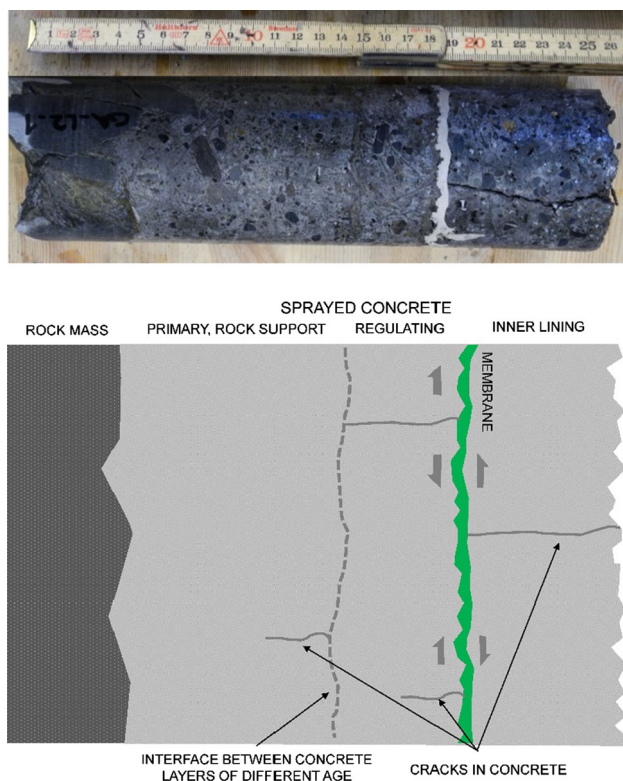


Fig. 3 Shear deformation and elongation at cracks of the membrane in the lining structure. *Top* photo showing persistent shrinkage crack in the secondary lining being bridged by the membrane. *Bottom* model for cracks and shear deformation

reinforcement and the restraint caused by the bond to the membrane will have some crack width reduction effect. Measurements of crack widths in the concrete lining has been conducted (Sect. 4.5 in this paper) in order to substantiate typical crack widths.

3.2 Exposure to Moisture

The continuously bonded property of the waterproof SCL system implies that there is an exposure to the groundwater at the interface between the rock mass and the sprayed concrete. Both the constituent materials concrete and membrane exhibit capillary and hygroscopic properties. Thus, the in situ moisture content of the lining materials and its effect on the mechanical properties need to be accounted for. Moisture properties of the lining materials are shown in Sect. 6.1 in this paper. The measured in situ moisture content in the investigated tunnel linings is shown in Sects. 4.2 and 4.3.

3.3 Consideration of the Monolithic Character of the Lining

The mechanical performance of a continuously bonded SCL depends on the performance of the weakest element in

the lining structure. A tunnel lining based on two layers of sprayed concrete separated by a bonded membrane should ideally be considered as one structure for the entire lining thickness. For this reason, the tensile bonding strength of the membrane-concrete interfaces should not be significantly lower than the tensile bonding strength between the rock surface and the sprayed concrete. Tensile bonding strengths for sprayed concrete interfaces to the rock substrate vary highly depending on rock type and the type of surface, as well as the application and material details of the sprayed concrete. Measured values for tensile bonding strength for the interface between sprayed concrete and rock vary between 0.2 and 1.8 MPa (NCA 2011; BeFo 2014; Bryne et al. 2014b). The gravity induced tensile stresses would be approximately a factor of 100 times lower than the lowest recorded tensile bond strength of concrete against rock. For this reason it is reasonable to propose an acceptance criterion for tensile bonding strength for the membrane which is in the magnitude of relevant tensile bonding strength between rock and sprayed concrete. Norwegian and Swedish standards propose 0.5 MPa as a minimum required tensile bond strength between rock and sprayed concrete. The ITAtech Design Guidance (ITA/AITES 2013) for sprayed membranes proposes an acceptance criterion of 0.5 MPa for tensile bonding strength.

3.4 Exposure to Freezing

The basic SCL design in our study has no insulating layers to avoid freezing exposure. The aim of this study is to determine the possible damage or reduction in performance caused by realistic freezing exposure. Given a membrane thickness of 3–4 mm, the thermal conductivity of the concrete material in secondary lining will be decisive for the thermal exposure. Each tunnel will represent an individual case with respect to freezing exposure based on the rock mass temperature, the winter climate, the ventilation of the tunnel and the location in the tunnel considered.

4 Field Investigations

4.1 Overview, Goal

The main goal of the field investigations was to substantiate as much as possible the loading conditions for the membrane (moisture, thermal and crack situation), as well as carrying out in situ measurements of the tensile bonding strength of the interfaces between the membrane and the concrete. We have included the investigations carried out on the large scale laboratory lining structure as part of the field investigations in this paper since this investigation

context has proven to cover comparable conditions to in situ tunnel. The field investigations were carried out in the period 2012–2014. Table 4 shows an overview of the conducted field investigations with locations and main purposes. The 4 locations and type of test sites are described in further detail in Holter and Geving (2015).

4.2 Moisture Content of the Tunnel Lining Structure

A detailed study of the moisture content and moisture transport mechanisms in waterproof SCL sections has been reported by Holter and Geving (2015). The findings of this study serve as an important basis for the analysis of the performance of the membrane described in this paper. The field investigations of the moisture content were carried out in three different tunnel sites at yearly intervals with ages up to 4 years. Several consistent observations were made during these investigations. The main features are:

- High degree of capillary saturation (DCS) of the concrete material, close to 100 %, at the rock-concrete interface.
- A gradient with decreasing DCS towards the lining surface.
- Depending on the lining thickness, the DCS of sprayed concrete on either side of the membrane is found to vary between 80 and 95 %. For primary (rock support) lining thickness of approximately 150 mm the DCS of the concrete at the membrane was found to be around 95 %.

The found moisture condition of the investigated linings can be explained by moisture transport processes from common building physics principles. Further details are given in Holter and Geving (2015).

4.3 Moisture Content in the Membrane Material

In addition to the investigations of the concrete material in the tunnel linings, also the membrane material was analyzed. Immediately after splitting of the cores, samples of the membrane material were removed from the concrete and tested for moisture content. Membrane samples from four different tunnel lining locations have been taken from 5 up to 38 months after construction. The measured values for moisture content, given as weight of water in % of dry weight of the membrane material are shown in Fig. 4. Dry weight of the membrane refers to weight after drying of 3–4 mm thick specimens at 105 °C for a minimum of 2 days.

A trend with decreasing moisture content in the membrane material with increasing time after construction can be observed, in spite of high degrees of capillary saturation of the concrete on either side of the membrane. These data refer to four different hard rock tunnel projects indicated with the different colors. The tunnel linings in all four cases were constructed with drained invert and waterproof undrained SCL in the walls and crown. The Karmsund case is a subsea road tunnel located at approximately 70 m below the groundwater table. Hence a complete saturation under hydrostatic pressure of the rock mass, and higher saturation of the imperfections of the concrete is likely to have taken place.

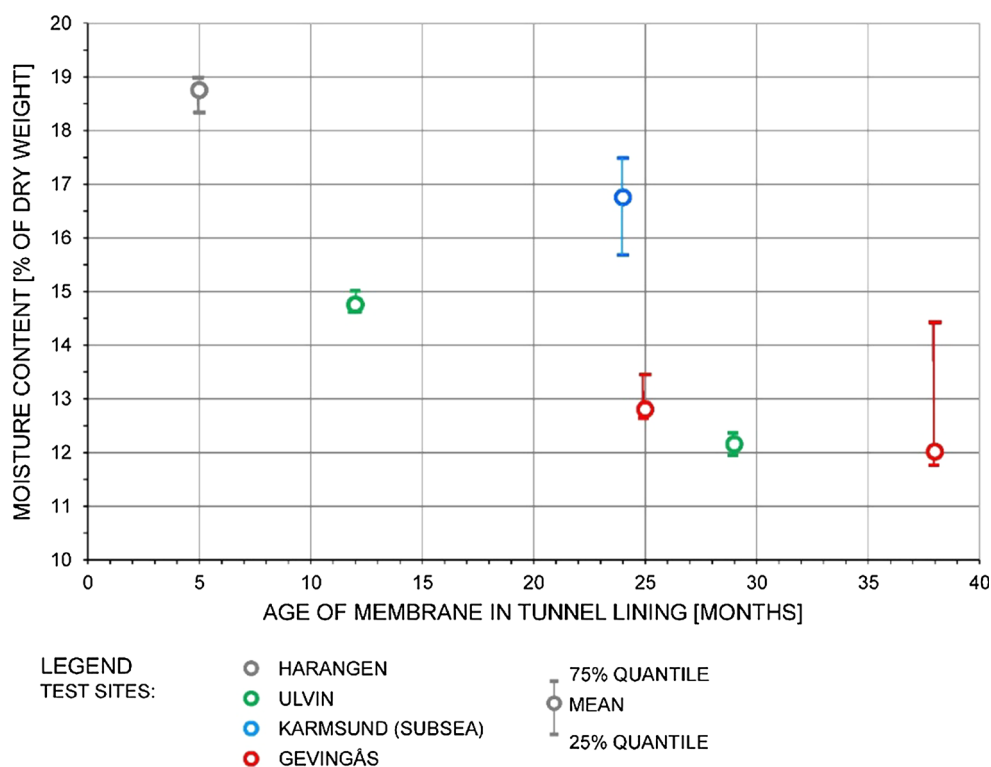
4.4 Thermal Exposure to Tunnel Linings

The rock and concrete materials exhibit thermal conductivities which govern the temperature profile from the rock mass to the lining surface under a given thermal exposure in the tunnel space. In this study, monitoring of temperatures under freezing exposure at full scale conditions,

Table 4 Overview of conducted field investigations for sprayed waterproofing membranes

Investigation	Location, test site	Main purpose of investigation
Moisture exposure and in situ moisture content, development over time	Gevingås Harangen Ulvin Karmsund	Basis for moisture conditioning during laboratory testing. Basis for assessment of degradation mechanisms
Mapping of cracks in sprayed concrete linings	Gevingås	Obtain realistic crack data for sprayed concrete
In situ tensile bonding strength	Ulvin Gevingås Laboratory lining structure	Tensile bonding strength under real exposure
Freezing exposure parameters	Ulvin Laboratory lining structure	Thermal profile through lining during severe freezing exposure

Fig. 4 Measured development of in situ moisture content in sprayed membrane material in tunnel linings



measurements of thermal conductivities of rock and concrete materials and thermal calculations were carried out. Thermal conductivities for sprayed concrete and intact rock were measured in a separate study (NTNU 2013). Some of the findings are shown in Table 5.

Thermal monitoring with freezing exposure was carried out in the full scale lining section at the Ulvin test site and the lining structure in the freezing laboratory. The main goal of this monitoring was to measure temperature profiles under realistic conditions. The temperature at the location of the membrane can then be assessed. The two monitoring cases are explained in Fig. 5.

The two test sites for thermal monitoring have the following main characteristics:

Case 1: Test site Ulvin, an access tunnel under construction with a test field of 90 linear m with SCL, with lining thickness 300 mm and membrane location at 150 mm from lining surface. The ventilation at the monitoring location was arranged with a gate in the tunnel so that air with a constant temperature of approximately 2 °C from the tunnel face (located more than 2 km in rock mass with constant temperature) could be alternated with cold air from outside. In this way an

Table 5 Measured thermal conductivities

Material	Density (kg/m ³)	Thermal conductivity (W/m K)	COV
Rock, dark gneiss (Ulvin site)	2616	2.95	0.3–0.5 %
Rock, granodiorite (Trondhjemite, freezing laboratory)	2657	2.77	0.2 %
Sprayed concrete, Ulvin site, steel fiber ^a , dry ^b	2138	1.64	0.5–1 %
Sprayed concrete, Ulvin site, steel fiber, saturated ^c	2214	1.85	0.2–0.5 %
Sprayed concrete, Gevingås site, PP-fiber ^d , dry	2211	1.65	0.5–1 %
Sprayed concrete, Gevingås site, PP-fiber, saturated	2281	1.85	2–3 %

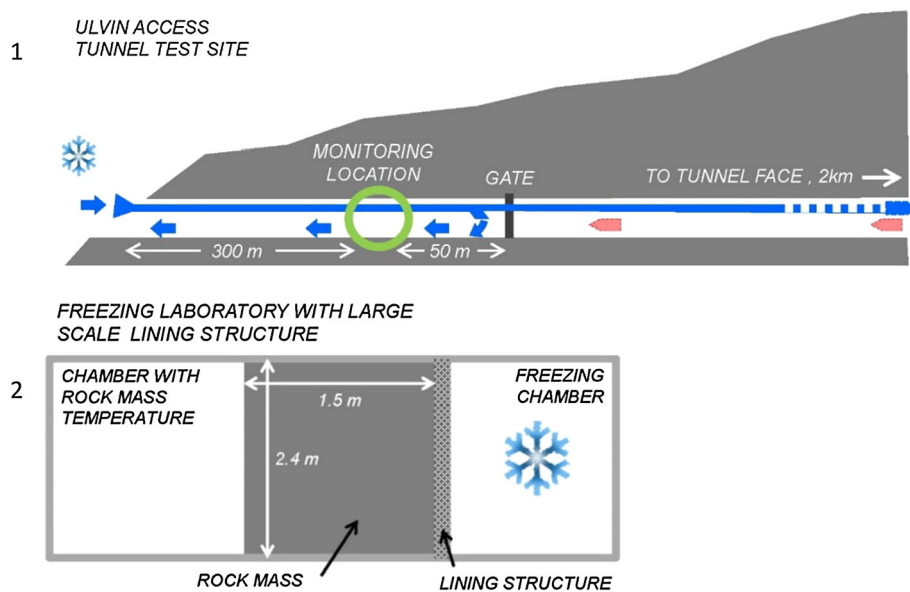
^a Steel fiber, dosage 35 kg/m³, 0.5 % by volume

^b DCS 70 %

^c DCS 100 %

^d Structural polypropylene fiber, dosage 7 kg/m³, 0.8 % by volume

Fig. 5 Longitudinal vertical sections with configuration of the Ulvin test site for in situ measurements (case 1) and the laboratory lining structure (case 2) for controlled thermal exposure



exposure to cold air at approximately 50 m distance from the portal could be applied experimentally in full scale. The field test at the Ulvin site could only be carried out in a short period of time for one severe freezing cycle over 36 h and hence, provided no information of long term freezing exposure.

Case 2: Laboratory test facility with large scale lining structure constructed on a rock mass of homogenous granodiorite blocks with lining thickness 240 mm with membrane location at 110 mm. Controlled freezing exposure was applied to the lining surface, simulating different freezing scenarios. Exposure modes included cyclic loads for accelerated freeze–thaw testing of the lining materials, and as isothermic exposure in order to simulate the effect of long term cooling of the lining.

Findings from an investigation conducted in the Glöddberget rail tunnel in north Sweden indicate that low air temperatures can penetrate far into the tunnel (STA 2012). The first 200–300 m from the portal can be exposed to air temperatures in the range of -15 to -20 °C in severe cases. The design of the tunnel lining for thermal insulation in portions with such severe exposure need to be evaluated in each single case based on local climate conditions and ventilation of the tunnel under operation during winter season.

The field test at the Ulvin site was arranged to produce a cooling of the tunnel lining by running the ventilation at approximately 1 m/s air flow with cold air from outside. Temperatures in the tunnel air at the test location in the range of -7 to -9 °C were achieved. After 36 h the test had to be terminated due to the tunnel construction cycle. A profile of the tunnel lining with the measured temperatures after 36 h is shown in Fig. 6. The calculated temperatures at steady state conditions with -7 and -9 °C in the tunnel

space are indicated. The measurements indicate a background temperature of the rock mass at the location of the tunnel of approximately 7 °C.

A large scale simulation of isothermic freezing exposure with -6 °C in the tunnel space was carried out on the lining structure in the freezing laboratory (case 2, Fig. 5). This exposure was held constantly for 30 days with continuous thermal monitoring. The results are shown in Fig. 7. The measured temperature profiles after 36 h and 17 days together with a calculated temperature profile at steady state are indicated. The measured values refer to three different sets of sensors in the lining–rock mass structure, and hence exhibit a slight scatter due to precision of location.

Based on the conducted freezing exposure tests, and calculation of temperatures at steady state conditions, the minimum temperature exposure at the membrane at given lining thicknesses can be assessed, Table 6.

4.5 Mapping of Cracks in the Sprayed Concrete

A mapping of cracks was carried out in the Gevingås rail tunnel on the 2nd August 2013, after an extended period of warm weather with maximum outdoor temperatures in the range of 25–30 °C. The temperature of the tunnel lining at 10 mm depth measured during the mapping of the cracks was 12 °C. Approximately 210 cracks were mapped and marked using a concrete crack width gauge (Fig. 8) in a systematic manner in order to re-record the same cracks later. Hence, the crack mapping was repeated at the exact same location in February 2014 when the temperature was 6 °C at 10 mm depth.

The measured crack widths are shown in Fig. 9. Crack widths ranging from 0.05 to 0.2 mm account for 78 % of

Fig. 6 Large scale laboratory simulation: measured and calculated temperature profiles through rock mass and lining structure

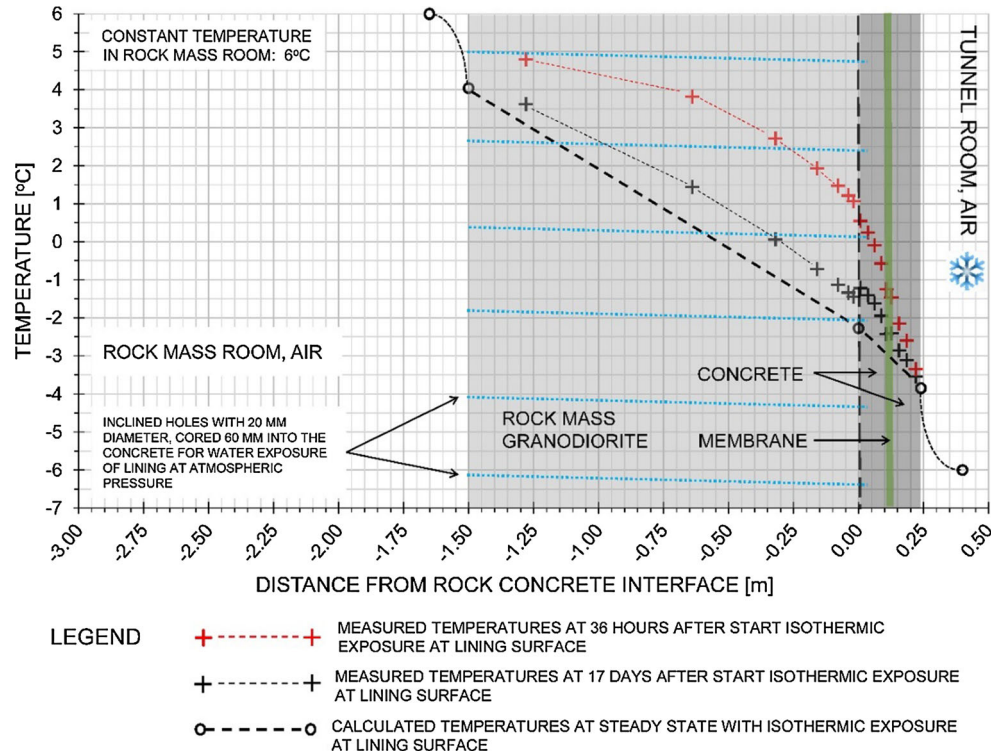
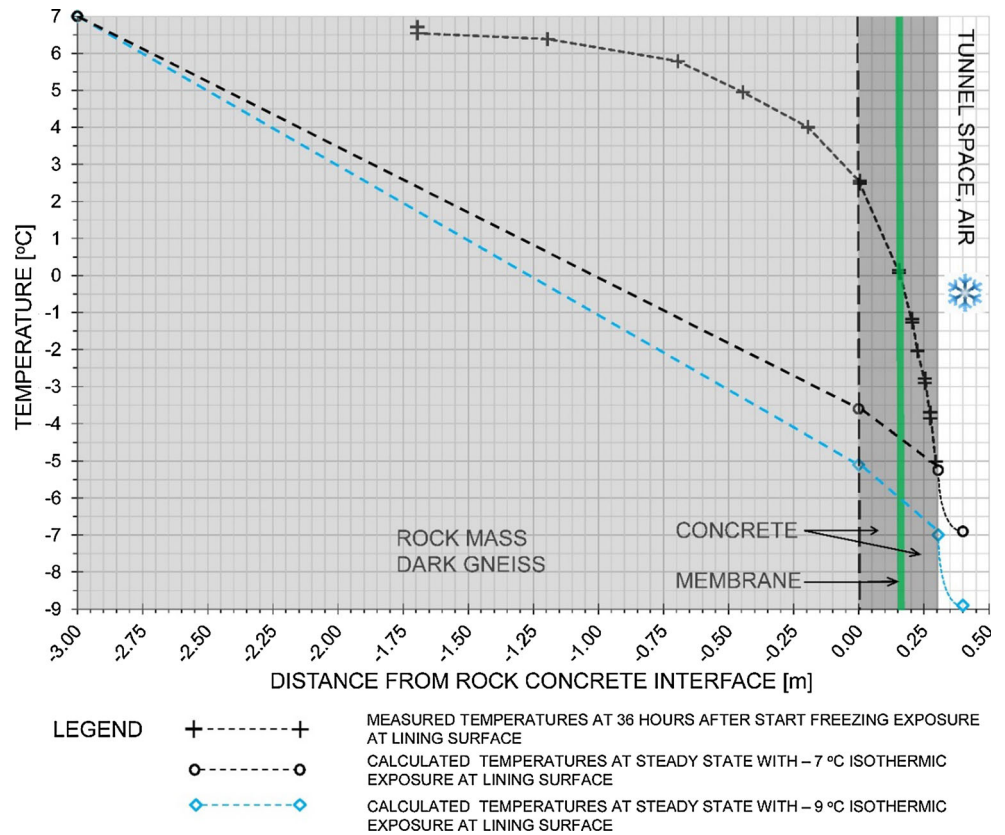


Fig. 7 In situ tunnel, Ulvin test site: measured and calculated temperature profiles through rock mass and lining structure



the recorded cracks for the measurements done in August 2013. The crack measurements in February 2014 show an increase in crack width, and a larger scatter of the

recordings. The most represented crack width for the measurements conducted in February is approximately 0.3–0.35 mm. Thus, an average increase in crack width of

Table 6 Temperatures at the location of the membrane in an SCL structure based on measurements and thermal calculations at steady state

Air temperature in tunnel space (°C)	Thickness of covering layer of sprayed concrete over membrane (mm)	Temperature at membrane (°C)
-6	110	-3.5
-7	150	-4.5
-9	150	-6



Fig. 8 Example of recordings of cracks in a sprayed concrete surface using a concrete crack measurement gauge

approximately 0.2 mm with a temperature decrease of 6 °C is observed. A typical crack pattern was obtained by observing the sprayed concrete lining surface in an area which exhibited leaks and showed mineral stains from leaks through wet cracks. This is shown in Fig. 10. Visible crack distances vary from approximately 0.2 m up to approximately 1.5 m. The most represented crack distance is in the range of 0.7–1 m.

4.6 Summary of Field Investigations, Verification of Loading Model

The loads which expose the membrane considered in this study are summarized in Table 7.

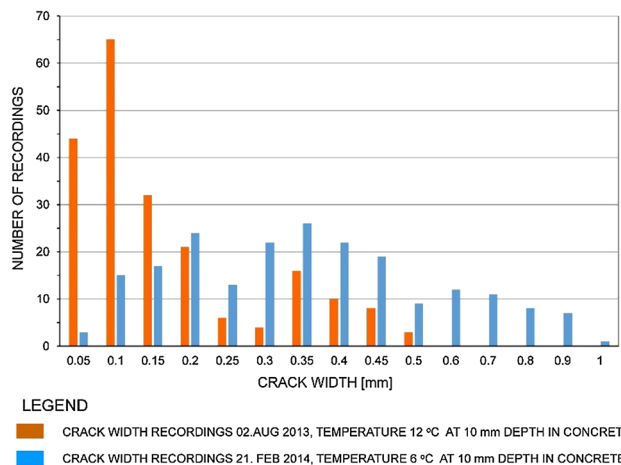


Fig. 9 Measured crack widths in the sprayed concrete lining surface at the same location in August 2013 and February 2014

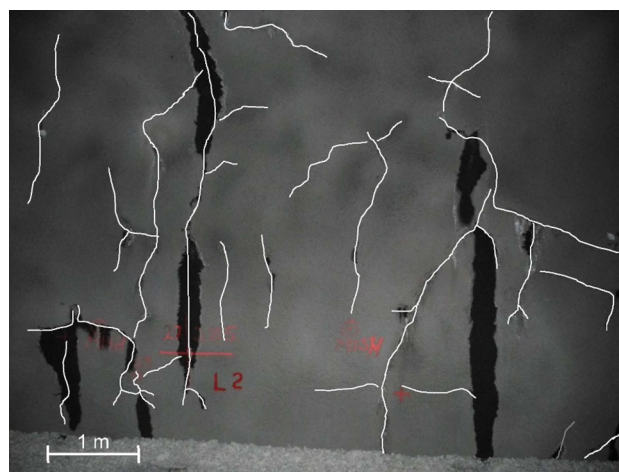


Fig. 10 Surface observations of cracks in sprayed concrete

5 Evaluation of Laboratory Test Methods

The main purpose of the laboratory test methods is to conduct material testing of the membrane under realistic loading and climatic exposure. There are several standardized test procedures for building materials which may be used for membrane materials. The most updated compilation of suggested tests is given in ITAtech Design Guidance for Spray Applied Waterproofing Membranes (ITA/AITES 2013). However this guidance has no loading models, neither any guidelines for mechanical, thermal nor moisture exposure testing of the membrane material. In this section the loading model (Sect. 3) and findings from the field investigations (Sect. 4) will be used to substantiate details in the laboratory test methods and relevant acceptance criteria.

Table 7 Compilation of loads on the membrane considered in this study

Load type	Relevant value/size	Implication for laboratory testing
Rock mechanical loads	None. Only local loads	None
Groundwater pressure induced loads	Very unlikely for the investigated cases. Not considered	None for cases with low or no hydrostatic pressure
Dynamic loads from traffic area	10 kPa amplitude of air pressure (pressure + suction loads)	None
Tensile loads	Gravity induced load from inner lining: 2 kPa	Not realistic requirement
Maximum crack width in concrete and thermal opening/closing	Typical crack width range: 0.1–0.3 mm, maximum 0.8 mm Thermally induced opening and closure : 0.6 mm	Testing of elasticity under relevant temperatures and moisture contents required Crack bridging performance at 1 mm crack width proposed
Shear deformation along interfaces	0.5–0.6 mm/m	1 mm shear deformation within linear shear elasticity behavior
Moisture exposure	15–18 % moisture content range in the membrane material	Pre-conditioning of membrane to relevant moisture content
Thermal exposure	Possible temperature range +15 to –6 °C at membrane location in tunnel lining	Testing at realistic temperatures

5.1 Moisture Properties of Lining Materials

Due to the hygric continuity of the lining structure and the direct exposure to groundwater, the moisture properties of the lining materials need to be included in order to substantiate the realistic moisture condition for testing. Recent reported testing of membranes for waterproof SCL (Su et al. 2013; Su and Bloodworth 2014; Nakashima et al. 2015) 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 have yet to be included in guidance for design and testing of spray applied membranes. Standard test methods for sorptivity and moisture content at equilibrium commonly used for concrete are adopted in this study. Thus, comparison to findings from other studies of concrete is possible.

5.2 Elasticity and Crack Bridging Properties of the Membrane

Preventing water flow through the lining by the bridging of cracks is the main waterproofing function of the membrane. Testing of the membrane's elasticity can be done by a pure elastic test or by a functional test of the resistance to rupture over a discontinuity in the substrate. Rupture of the membrane over a crack with increasing width is found to be the main failure mechanism in the loading model (Sect. 3). Hence, the crack bridging test as proposed in the ITAtech guidance (ITA/AITES 2013) guidance directly addresses a relevant failure mode. A pure elasticity test does not account for the bonding of the membrane to the

substrate. It is difficult to quantify a requirement in terms of pure elasticity which translates to the required crack bridging capacity. However, the elasticity test is simple and can give an indication of the elasticity of the membrane material in order to reject unsuitable materials without conducting costly testing.

5.2.1 Elasticity Testing According to DIN 53504

This is a simple test conducted on specimens with standard dimensions which are stretched to failure while measuring tensile deformation and tensile force. Standard dog bone shaped specimens, shown in Fig. 11, have normally been used for this purpose. The sensitivity of EVA-based membranes to moisture content means that details regarding storage and conditioning as well test procedure for such membranes needs to include details regarding humidity and temperature. Sprayed specimens are preferred to molded specimens in order to test realistic membrane material. However, sprayed specimens are more difficult to produce with even thicknesses for the purpose of reproducing consistent standard dimensions for laboratory testing.

5.2.2 Crack Bridging Performance

The proposed test method for crack bridging performance according to ITA/AITES (ITA/AITES 2013) is a static crack bridging test and is designed for the testing of coating materials on exterior surfaces of masonry and concrete (DIN EN 1062-7:2004). With this test method one can basically test only one crack width, although it would be possible to include a few increments in the crack width

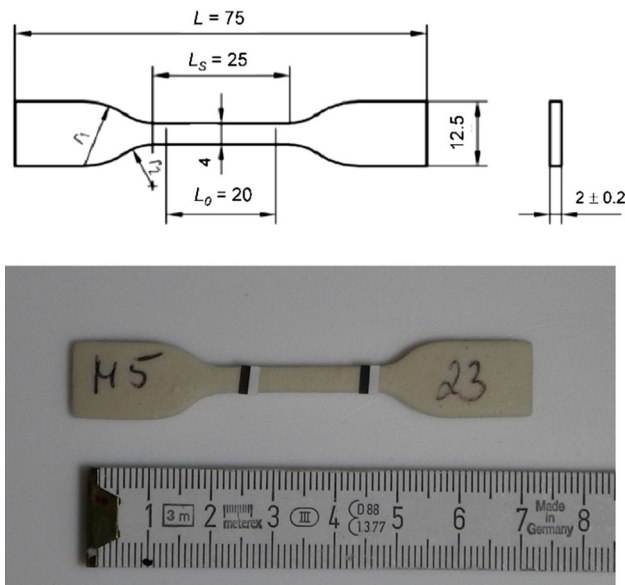


Fig. 11 Specimen for elasticity test according to DIN 53504. *Top* dimensions of the S2-type dog bone shaped specimen used for this purpose, with figures in mm. *Bottom* photo of specimen with markings of the length L_0 area for precise elongation measurement with video-extensometer

before the maximum crack width, given by the geometry of the test jig, is reached. The main features of this test method are shown in Fig. 12.

An adjusted crack bridging test has been considered in order to apply a more controllable opening of the crack and hence enable a precise determination of the crack width at rupture. This adjusted test method has many similarities to the dynamic tensile test described in DIN EN 1062 Annex C4. The adopted procedure is shown in Figs. 13 and 14.

5.3 Tensile Bond Strength

Testing of tensile bond strength, also referred to as pull-off strength or adhesion, of sprayed membranes has been conducted by pulling the membrane off the substrate (Ozturk and Tannant 2010). This procedure uses a disc shaped plate mounted on an elevator bolt which is glued to an over-cored section of the membrane and subsequently pulled in a controlled manner. This method can prove useful for a temporary test of the membrane’s tensile bond strength before the inner lining concrete is applied. Testing of tensile bonding strength of the membrane in the lining structure as proposed by ITA/AITES (2013) is a standard pull-off test for adhesion including the entire lining structure, according to EN ISO 4624 section 9 (2003). The principle of the test is shown in Fig. 15. However, the wet core drilling, the risk of applying unfavorable bending and tensile loads during the core extraction, inconsistent

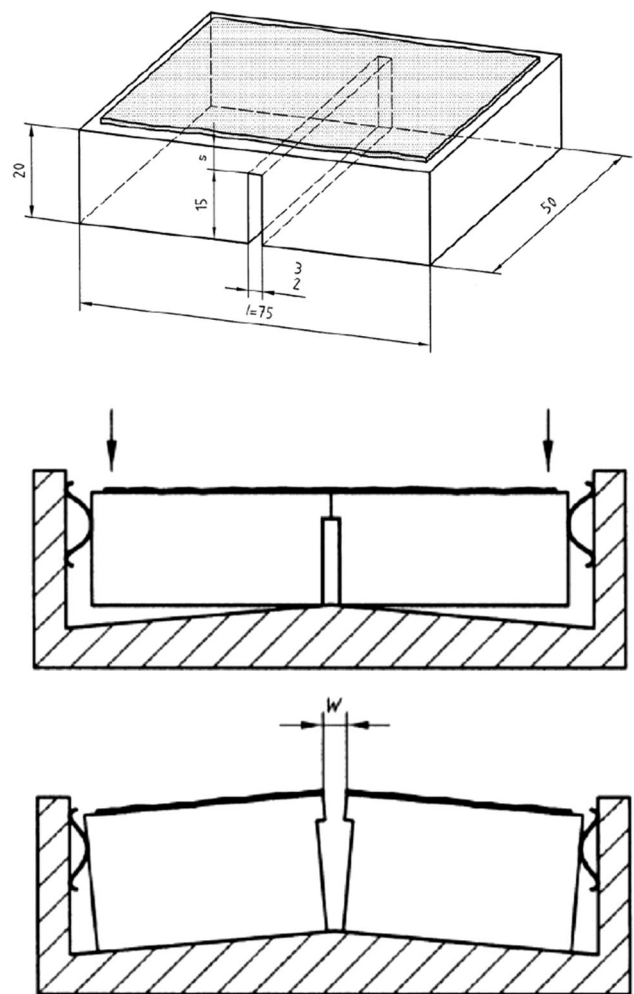


Fig. 12 Conceptual illustrations showing the static crack bridging test procedure according to DIN EN 1062-7 Annex C1, proposed by ITA/AITES 2013

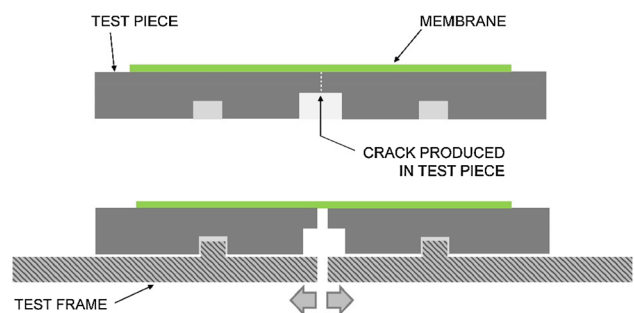


Fig. 13 Conceptual illustrations showing the loading mode during the adopted version of the dynamic crack bridging test

moisture conditioning and details in the test setup might influence the results significantly.

A procedure to measure tensile bond strength without extracting core samples was adopted. The main purpose of this procedure was to test the tensile bond strength under as



Fig. 14 Crack bridging testing with adopted procedure in progress in climate chamber. (Courtesy by Wacker Chemie AG)

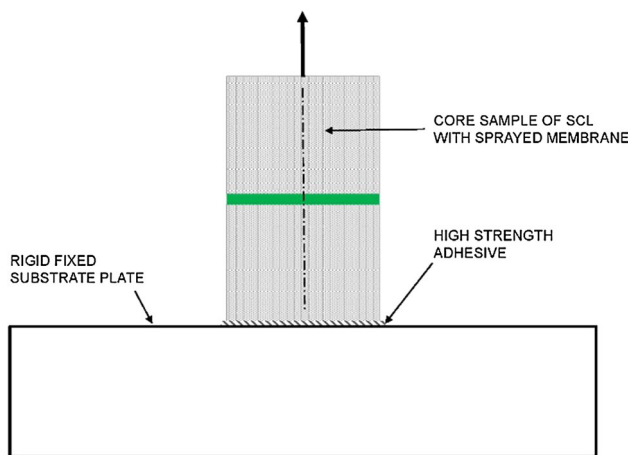


Fig. 15 Testing of tensile bonding strength according to EN-ISO 4624

realistic conditions as possible. The procedure was laid out as an in situ test in which the test specimen consisted of an over-cored part of the lining structure. The layout of the pull-off details were arranged in order to achieve a perfect axial alignment to the core specimen. The adopted test is shown in Fig. 16. The testing device used in this investigation could only record maximum tensile strength.

5.4 Shear Performance of the Membrane-Concrete Interfaces

Direct shear testing is not proposed by ITA/AITES (2013). Direct shear testing is included in this study in order to establish the membrane's ability to perform under shear deformation which can occur between the substrate and inner lining concrete layers. Previous direct shear testing of such membrane concrete interfaces has been reported by

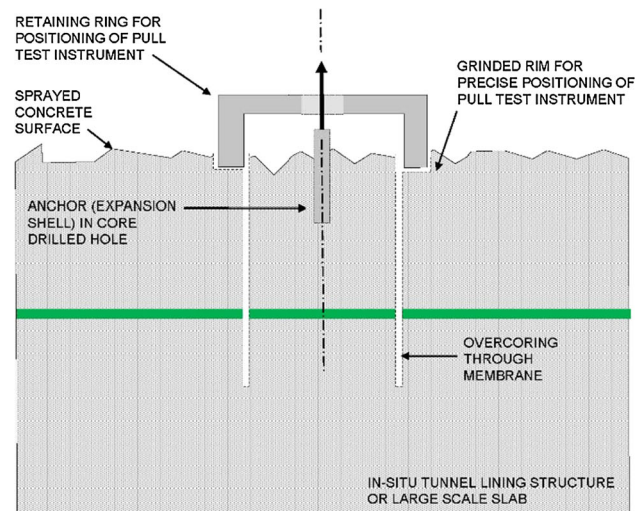


Fig. 16 Adopted procedure for in situ measurements of tensile bonding strength. *Top* conceptual diagram showing the layout of the test. *Middle* Preparation with over-coring with grinding of the test specimen. *Bottom* in situ specimen after testing

BASF (TU Graz 2008), Su et al. (2013) and Su and Bloodworth (2014). These investigations refer to EVA based sprayed membranes in which the specimens were tested in dry state without any pre-conditioning to relevant moisture content. A study of the composite action of EVA-based membranes for SCL was carried out by Nakashima

et al. (2015). However, this study also considers a lining structure and the membrane material in dry condition.

For our study a large scale shear box with constant normal load was available. Controlling the normal load in order to apply constant normal deformation or constant normal stiffness was not possible in our study. The test procedure and moisture conditioning of the specimens is explained in Sect. 6.6 together with the obtained results.

6 Conducted Laboratory Investigations

The laboratory investigation program was based on the conceptual model, the results from the field investigations and the evaluation of testing methods. The main goal of the laboratory investigations was to verify the conceptual model, establish detailed performance properties of the lining, as well as providing a basis for the acceptance of a membrane product under certain conditions.

6.1 Moisture Properties of Sprayed Concrete and Membrane Materials

6.1.1 Specimens

The specimens for the sprayed concrete testing of the moisture properties were all obtained from the tunnel lining from the same site and the same location, the Harangen test site (details in Table 1). Hence, the specimens represent the same concrete in terms of age, curing history, mix design and spray application. The membrane specimens were all produced from sprayed sheets, and tested after complete curing for approximately 18 months. The investigation of moisture properties in our study covers water content after immersion at atmospheric pressure, sorptivity (water absorption rate) and moisture

bearing capacity in the hygroscopic range. These are illustrated in Fig. 17.

6.1.2 Water Content at Immersion at Atmospheric Pressure

Membrane specimens obtained by core drilling specimens from sprayed panels as well as sprayed membrane specimens from spray sheet panels were tested. Results are shown in Fig. 18 and Table 8. For the membranes M1 and M5 the maximum water uptake potential is found to be approximately 42 and 30 % of the dry weight of the material. The water content at immersion for concrete at atmospheric pressure is assumed to be equal to the complete saturation of the suction porosity of the concrete.

6.1.3 Water Absorption Rate (Sorptivity)

Sorptivity expresses the water absorption rate under unilateral and unidirectional water exposure, and was investigated by Holter and Geving (2015). A compilation of the results for concrete and membrane M1 is shown in Fig. 19. The measured water absorption rate of the two materials exhibit a significant contrast within the moisture content range which is found in tunnel linings.

6.1.4 Moisture Content at Equilibrium in the Hygroscopic Range

The investigation of the moisture content at equilibrium for concrete was presented by Holter and Geving (2015). Testing of the membranes M1 and M5 with moisture content at equilibrium obtained by isothermic desorption has been added in this study. The desorption isotherms show moisture content represented as degree of saturation at immersion for the materials versus relative humidity. A compilation of the results is shown in Fig. 20. The difference in behavior when

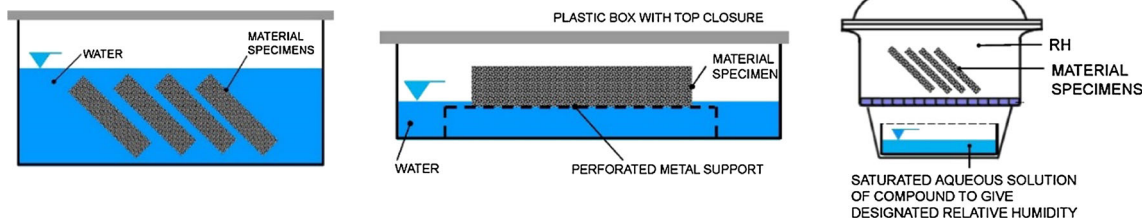


Fig. 17 Sketches of the three water absorption modes which have been tested in the laboratory. *Left* water content at complete immersion. *Middle* sorptivity (water absorption rate) at unidirectional

water exposure. *Right* moisture bearing capacity at equilibrium in the hygroscopic range

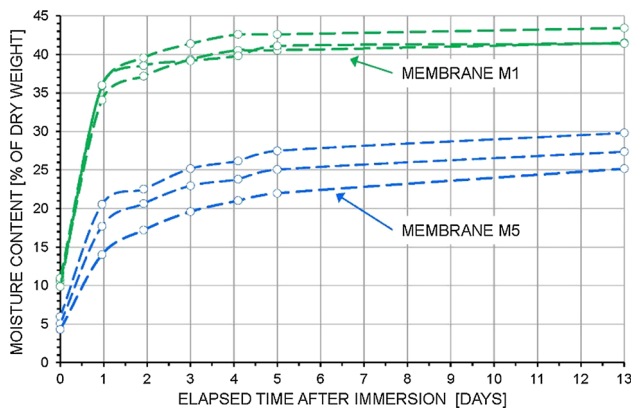


Fig. 18 Moisture content of membranes measured after complete immersion at atmospheric pressure for sprayed specimens of membranes M1 and M5

Table 8 Moisture contents at immersion for two series of specimens for membranes M1 and M5

Membrane product	Moisture content at immersion (weight % of dry weight)	
	Specimens obtained from lining structure slabs (Fig. 19)	Specimens from sprayed membrane sheets
M1	41.5	42.4
M5	27.4	30.3

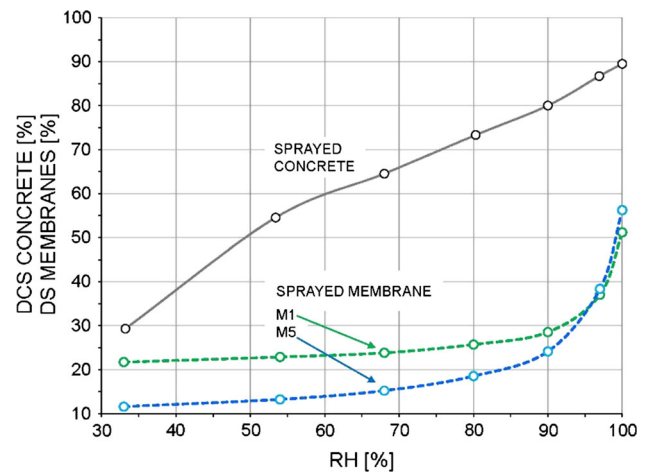


Fig. 20 Desorption isotherms obtained at 25 °C for sprayed concrete and sprayed membrane, showing the moisture content represented as degrees of saturation at equilibrium versus different values for RH

Table 9 Measured linear thermal expansion coefficient for steel fiber-reinforced sprayed concrete

Parameter	Mean (m/m K)	COV (%)	Temperature interval (°C)	Number of specimens
Thermal expansion coefficient	1.27×10^{-5}	1.6	3–19	3

of their moisture content. The desorption isotherms (Fig. 20) show that sprayed concrete is a much more hygroscopic material than the membrane material.

6.2 Thermal Expansion of Sprayed Concrete

Linear thermal expansion was measured on cut prism samples of sprayed concrete with dimensions 70 × 70 by 280 mm in different temperature intervals from 3 to 34 °C. The measured values for the temperature interval 3–19 °C are found to be the most relevant and are shown in Table 9. The mix design of the sprayed concrete is shown in Table 2, Sect. 2.

6.3 Elasticity of the Membrane Material, DIN 53504

6.3.1 Specimens, Conditioning and Testing Temperature

Specimens from both sprayed and molded sheets of membrane were prepared. Five membrane products were tested in three different test series, in three different laboratories. Altogether five membrane products were tested. Conditions during testing covered humidity conditioning at RH 50 and 95 % and at specific temperatures 23, 0, –3, –8

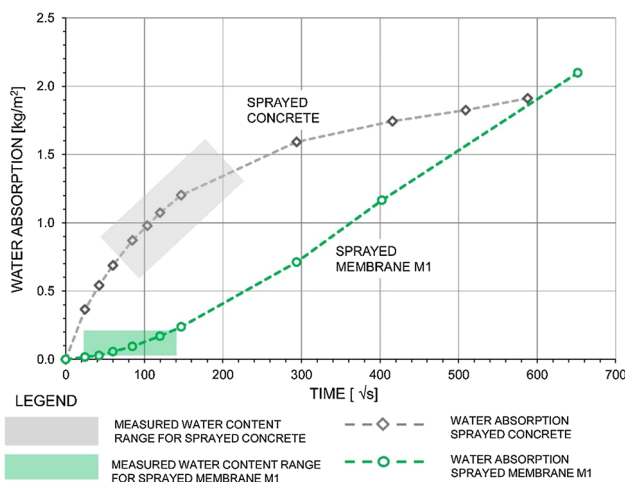


Fig. 19 Water absorption rate (sorptivity) of sprayed concrete and sprayed membrane (M1) represented as water absorption versus square root of time (compiled from Holter and Geving 2015)

taking the material from immersion to RH 100 % is noteworthy. Concrete loses approximately 10 % of its moisture content, whereas the membranes lose approximately 50 %

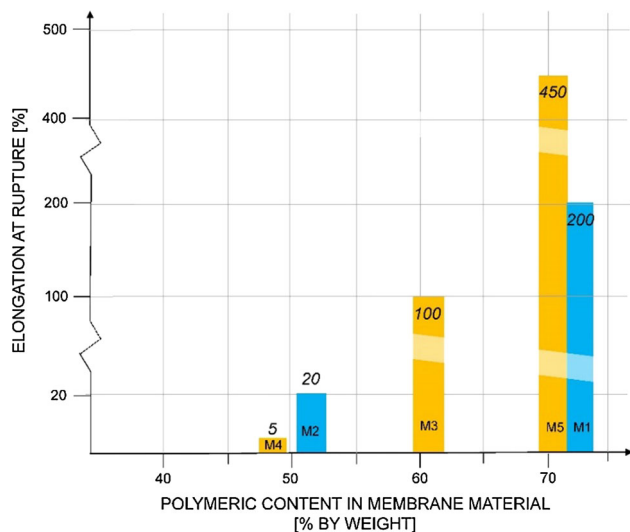


Fig. 21 Elongation performance of sprayed membrane samples versus polymeric content in the base (powder) membrane products M1–M5 measured by thermo-gravimetric analysis (TGA) with argon as test gas. The elongation was measured in one single test series (laboratory 1) with specimens which had undergone identical treatment from application to testing

and $-12\text{ }^{\circ}\text{C}$. A test of the polymeric content elasticity which could be related to the elasticity performance of the membranes was also carried out.

Our findings using this test method show that it is difficult to obtain consistent results when comparing different test series. The main limitations were:

- Difficulty in preparation (spray application) of specimens with even thicknesses required for reproducible laboratory tests.
- The thickness and evenness of the membrane specimens influences the result significantly.
- Different storage conditions after application and the precise conditioning details influence the absolute measurement values.
- Different interpretation of the test standard regarding testing details.

Table 10 Initial test series of elongation carried out in Laboratory 1

Membrane (all sprayed)	Measured elongation at failure, mean (%)		
	No freezing, storage at $23\text{ }^{\circ}\text{C}$ RH 95 %	6 cycles ^a , freezing to $-20\text{ }^{\circ}\text{C}$ in air, thawing at $23\text{ }^{\circ}\text{C}$ RH 95 %	6 cycles ^a , freezing to $-20\text{ }^{\circ}\text{C}$ in air, thawing at $23\text{ }^{\circ}\text{C}$ immersed in water
M1	194	212	94
M2	20	22	18
M3	131	135	131
M4	4.3	4.9	6.2
M5	438	457	408

^a Freezing 24 h, thawing 24 h

6.3.2 Findings

For the first elongation test, the polymeric content of the membrane products was tested using a thermo-gravimetric analysis with Argon as test gas in the test vessel. The membrane material was heated to $800\text{ }^{\circ}\text{C}$. Hence, it was possible to record the weight loss due to pure evaporation of the components, considered to be the pure organic polymeric content. The results are shown in Fig. 21. The two colors indicate the two different suppliers of the membrane products.

The results of the initial test are illustrated in Table 10. Cyclic freezing and thawing in air has the effect of a slight increase on the elongation performance. When thawing under water between each freezing cycle membrane M1 shows approximately 50 % reduction in elongation performance, whereas the other membranes are unaffected by the freeze–thaw exposure.

The main findings from the conducted elongation testing can be summarized as follows:

- Within the same test series, a consistent trend of significantly decreasing elasticity with decreasing temperature has been observed.
- A relatively large scatter is caused by varying thicknesses of the membrane within the same specimen as well as specimens with different thicknesses.
- Conditioning at RH95 % gives higher measured elasticities compared to specimens conditioned at RH50 %.
- Elasticity mainly increases with increasing polymeric content (shown in Table 11).

6.4 Crack Bridging

6.4.1 Specimens

Specimens for crack bridging testing were produced by applying the membrane material on pre-fabricated test pieces of porous artificial sandstone (Fig. 22). Both spray-applied and molded membrane specimens were prepared. Three series of specimens, shown in Table 12, were

Table 11 Measured values for elongation for membrane according to DIN 53504 for two test series

Test location	Membrane sprayed/molded	Pre-conditioning	Measured elongation (strain) at failure, mean (%)				
			23 °C	0 °C	−3 °C	−8 °C	−12 °C
Laboratory 2	M1 sprayed	RH 95 %	45		38	10	5
	M5 sprayed		685		89	20	8
Laboratory 3	M1 sprayed	RH 50 %	20	9	6	0.6	
	M5 sprayed	RH 50 %	242	56	14	1.4	
	M1 molded	RH 50 %		71	31		
	M1 molded	RH 95 %	242	76	55		
	M5 molded	RH 50 %		21	9		
	M5 molded	RH 95 %	446	40	13		

prepared in order to cover a range of temperatures and moisture contents.

6.4.2 Procedure

The test method stated in DIN EN 1062 annex C4 dynamic tensile test, with the modifications developed by Wacker Chemie AG, described in Sect. 5.2.2 in this paper was

followed. The crack width was increased in increments of 0.2 mm every 5 min. Immediately before a crack width increase was applied to the specimen, the membrane surface was visually inspected and deemed intact or ruptured. Any sign of initial rupture was interpreted as membrane failure (Fig. 23).

6.4.3 Results

The results of test series 1 and 2 are shown in Fig. 24. For the specimens with spray applied membrane (series 1) values are shown as mean with 25 and 75 % percentiles. For the molded specimens (series 2) only average values are shown, since there were too few satisfactory readings to obtain statistical data. The specimens had slightly differing membrane thicknesses. Therefore the value for rupture was given as the ratio between crack width at rupture and the membrane thickness which varied from 1.9 to 5.5 mm. The variation of the membrane thicknesses was largest for the specimens with spray applied membrane. The results (Fig. 24) show that the crack bridging capacity decreases with decreasing temperature with the given conditioning of the specimens. Both membrane products M1 and M5 were found to bridge cracks with an aperture in the range of 0.4–0.8 times the thickness of the membrane at −8 °C. At

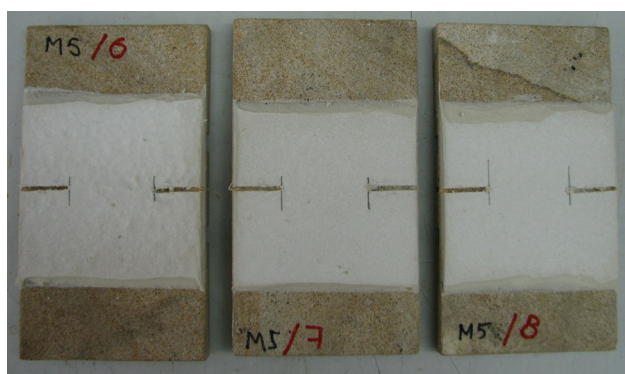


Fig. 22 Specimens for crack bridging test with membrane applied on the surface of test pieces. The dimensions of the test pieces are 100 mm × 200 mm

Table 12 Matrix for conducted testing of crack-bridging

Test series number	Membrane, sprayed/molded	Conditioned at RH (%)	Temperature at testing, number of specimens tested			
			23 °C	0 °C	−3 °C	−8 °C
1	M1 sprayed	95	3	2	3	3
	M5 sprayed	95	3	3	3	3
2	M1 molded	50		3	3	
	M5 molded	50		3	2	
3	M1 molded	95 ^a		3	3	
	M5 molded	95 ^a		3	3	

^a Cured in RH 95 % for 28 days immediately after molding prior to testing

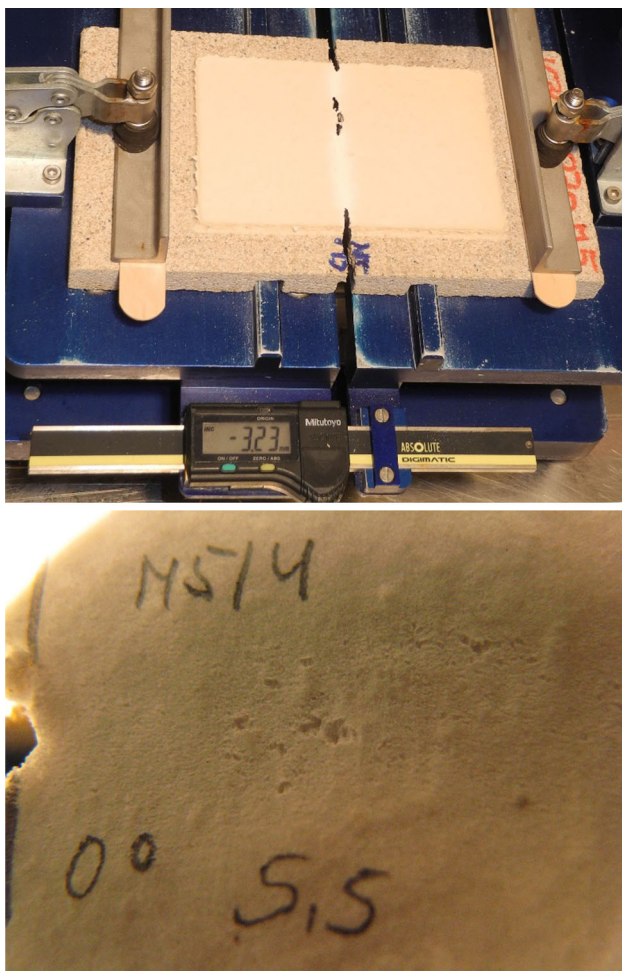


Fig. 23 Crack bridging testing in progress. *Top* specimen in testing apparatus for precise measurement of crack aperture at rupture. *Bottom* definition of rupture with visible initial damage of the membrane

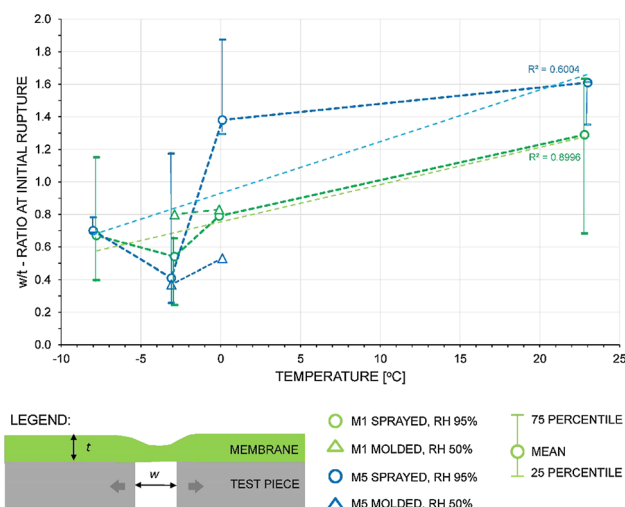


Fig. 24 Results from crack-bridging testing for membranes M1 and M5 conducted at different temperatures and pre-conditioned at RH 50 and 95 %

23 °C the two membranes M1 and M5 were to bridge cracks with an aperture in the range of 1.3–1.6 times the thickness of the membrane. Series 3, tested only at 0 and –3 °C with molded specimens cured and pre-conditioned at RH 95 % for 28 days after application, did not exhibit any rupture at 11 mm which is the maximum crack width which the machine could produce. This indicates that the immediate curing after application at RH95 % leaves sufficient water in the membrane to act as a “softener” with resulting high elasticity.

6.5 Direct Shear Tests, Shear Bond Strength

6.5.1 Specimens

The specimens were produced from square panels using poured concrete with typical sprayed concrete mix design and spray applied membrane. In this way regular interfaces were achieved. The panels were stored under water for 5 months before specimens with 74 mm diameter were core drilled. The core specimens underwent another 30 days of storage under water. Throughout the storage under water a 40 mm wide strip strong tape was applied around the core completely covering the membrane and protecting it from direct water exposure. In this way the membrane only received exposure to water through the concrete pores.

6.5.2 Procedure

After water storage the specimens were prepared for shear testing by mounting them in a steel frame assembly. The process of preparing a series of three specimens in the test assembly and conducting the shear tests could be undertaken in 1 day. The assembly of the specimens is shown in Fig. 25 and the steps in the procedure are shown in Fig. 26.

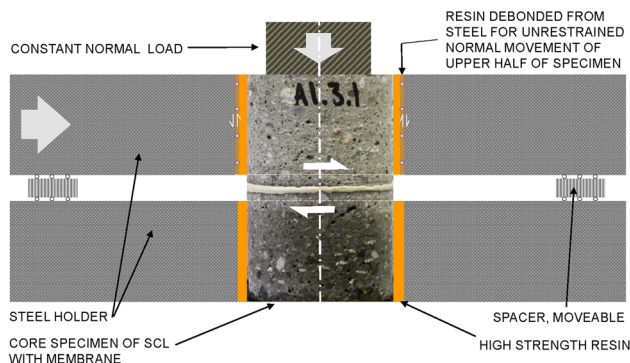
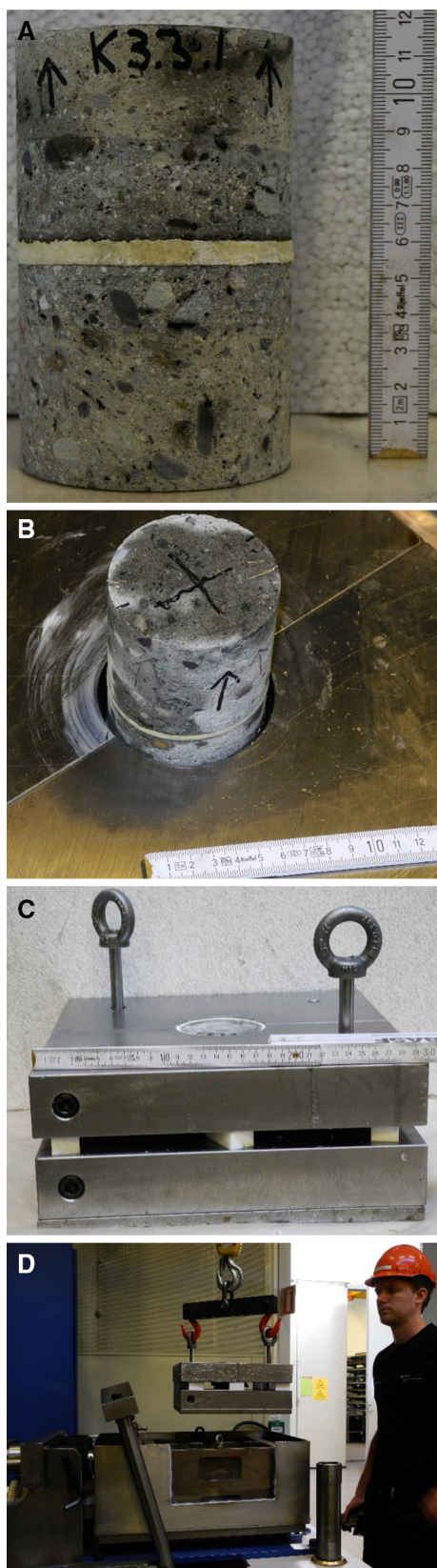


Fig. 25 Conceptual diagram showing a section of the assembly with core specimen mounted in the steel frame used for direct shear testing



◀**Fig. 26** Direct shear testing of SCL structure. **a** Typical core specimen with 74 mm diameter. **b** Specimens placed in steel holder ready for fixing with high strength resin. **c** Specimen in complete assembly ready for testing. **d** Placement of test assembly into shear box

Table 13 Conditions for shear testing

Parameter	Condition
Shear loading	Constant displacement, 0.5 mm/min
Normal loading	Constant normal load, 0.45 MPa
Measured parameters during test	Shear displacement, normal displacement, shear load
Age of specimen at testing	180 days

Details regarding the testing procedure are shown in Table 13.

6.5.3 Results

The results are presented as shear-stress versus shear displacement diagrams, providing the following information:

- Peak shear stress for the specimen.
- Shear displacement at peak stress.
- Maximum shear displacement within linear elastic behavior.
- Shear stiffness during linear elastic behavior.

The results for membrane M1 are shown in Figs. 27 and 28 and for membrane M5 in Figs. 29 and 30. A compilation of the recorded data is shown in Table 14.

Both membranes exhibit almost the same behavior within the initial deformation, showing linear shear elasticity up to approximately 1 mm shear deformation. Membrane M1 exhibits a slightly higher shear stress at this point, corresponding to the higher shear stiffness K_1 compared to M5. M1 exhibits a clear bonding (adhesive) failure (Fig. 28) with peak shear stresses in the range of 0.55–0.85 MPa, after approximately 3–4 mm shear deformation. After the initial zone of shear elasticity, the two membranes have very different behavior. Membrane M1 exhibits increasing strain softening behavior and membrane M5 exhibits a bi-linear behavior with increased displacement. In the latter phase a lower shear stiffness can be observed. After approximately 7–8 mm horizontal displacement membrane M5 exhibits almost

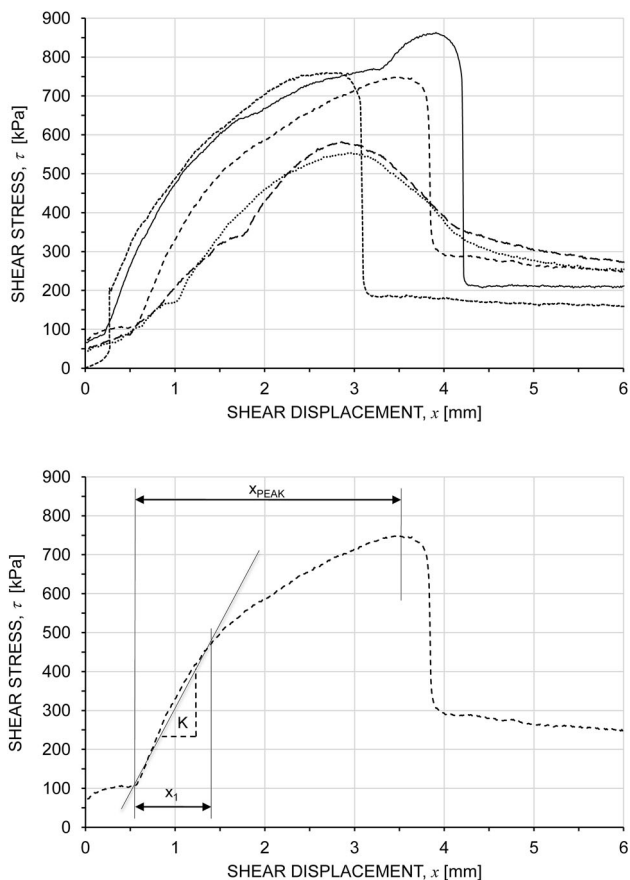


Fig. 27 Results from shear testing for membrane M1 represented as shear stress versus shear displacement. *Top* diagram showing results for all five specimens. *Bottom* results for one specimen with recorded parameters, shown in Table 16



Fig. 28 Specimen of membrane M1 after shear testing exhibiting a debonding (adhesive) failure between membrane and the substrate concrete

perfect plasticity and reaches a peak shear stress of approximately 0.45–0.5 MPa. No clear failure could be observed during the shear testing with the M5

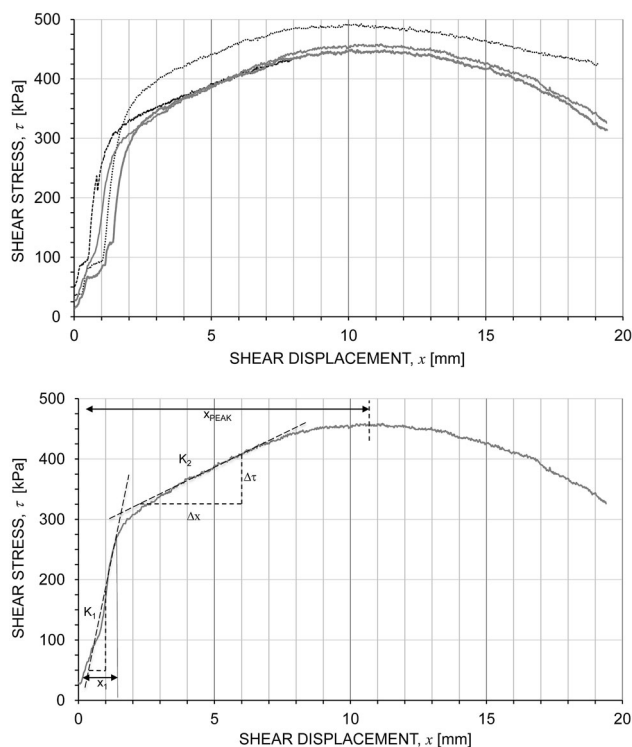


Fig. 29 Results from shear testing for membrane M5 represented as shear stress versus shear displacement. *Top* diagram showing results for all five specimens. *Bottom* results for one specimen with recorded parameters, shown in Table 15



Fig. 30 Specimen of membrane M5 after shear testing exhibiting shear (cohesive) failure in the membrane material

specimens. The tests for M5 were terminated after 19 mm of shear deformation. When removing the specimens from the test assembly, failure in the membrane could be observed since the upper and lower part of the specimen could easily be separated (Fig. 30).

Table 14 Compilation of results from direct shear testing of membranes M1 and M5

Membrane (number of specimens)	Shear displacement x : mean, mm (COV, %)	Shear displacement x_{PEAK} : mean, mm (COV, %)	Shear stiffness K1: mean, MPa/m (COV, %)	Shear stiffness K2: mean, MPa/m (COV, %)	Peak shear stress: mean, kPa (COV, %)	Membrane thickness range, mm	Measured moisture content in membrane, % (COV)
M1 (5)	1.0 (33)	2.5 (25)	350 (20)	n.a.	745 (16)	3.5–4	15.7 (10)
M5 (4)	1.1 (18)	9.0 (7)	297 (20)	19 (9)	450 (5)	4–6	14.5 (12)

6.6 Tensile Strength of Membrane-Concrete Interface

6.6.1 Specimens

Testing of tensile strength of the membrane-concrete interface was carried out in 4 different series (explained in Table 15), including laboratory tensile testing of 74 mm diameter core specimens drilled from panels, pull testing on panels with lining structure and in situ pull testing from full scale tunnel linings. The moisture content of the concrete and membrane materials of the specimens was measured whenever possible. The testing of the linings at the Gevingås and Ulvin tunnel sites was conducted parallel to the moisture condition sampling and testing. For the large scale laboratory lining structure (Fig. 7, Sect. 4.4) the moisture content of the sprayed concrete and membrane which was achieved after 6 months of moisture conditioning was found to be very close to the moisture content

measured in tunnels (Holter and Geving 2015). Hence, the laboratory lining structure could be used for controlled freeze–thaw testing with realistic moisture content.

6.6.2 Procedure

Both testing procedures described in Sect. 5.3 in this paper were followed. Test series 1 was conducted with the original method stated in EN-ISO 4624 on core specimens which were moisture conditioned by immersion for a minimum of 14 days and subsequently tested in a laboratory tensile pull machine. Test series 2 was conducted with the in situ tensile test method on slabs cut from slabs of lining structure. Prior to testing, the slabs received different pre-treatment types with moisture exposure at immersion and cyclic freezing and thawing. Series 3 and 4 comprise the tensile testing which was done on full scale lining structures, either in situ in tunnels or on the large scale

Table 15 Matrix for the different test series for tensile strength

Test series	Type of lining structure for specimens	Testing method	Membrane products tested	Conditioning and exposure of lining structure or specimen	Age at testing
1	Sprayed panels 600 mm × 600 mm	Drilled core specimens, tested in pull test machine	M1 M2 M3 M4	Dry Saturated by immersion for 14 days Frozen/thawed	12–14 months
2	Sprayed panels 600 mm × 600mm	Laboratory In situ pull tests conducted on panels	M1 M5	Dry Saturated by immersion for 60 days Frozen/thawed 6 times, –20/+20 °C Testing in frozen and thawed condition after freeze–thaw exposure	18–19 months
3	Full scale lining in tunnel (Gevingås and Ulvin test sites)	In situ pull tests in tunnel lining	M1	In situ moisture exposure in rock mass	Ulvin: 29 months Gevingås: 37 months
4	Laboratory lining structure on rock mass with water exposure and freezing	In situ pull tests in lining structure	M1	Moist without freezing exposure Moist frozen-thawed to –3 at membrane, tested after 20 and 35 cycles In frozen condition after 35 cycles	19–25 months

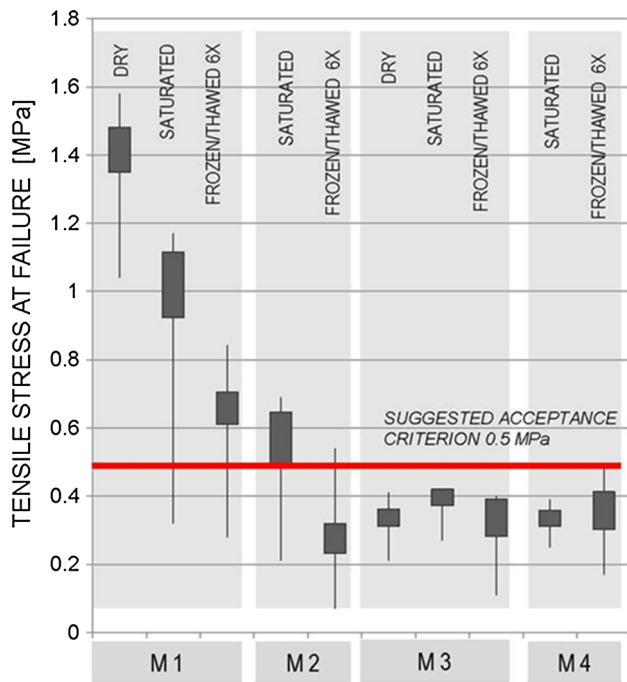


Fig. 31 Results from tensile bond tests for test series 1 (Table 15), drill core specimens with diameter 74 mm. Membrane numbers M1–M4 are explained in Sect. 6.3.2

laboratory lining structure. The adopted in situ tensile test method described in Sect. 5.3 was used for this purpose.

6.6.3 Results

The results for the first test series, which included the membranes M1, M2, M3 and M4 are shown in Fig. 31. With this testing method membrane M1 exhibits a range of strength reduction between 1.1–1.5 MPa tensile bonding strength (comparing dry specimens to saturated) and frozen/thawed specimens showed even more reduced tensile strengths. The scatter in measured tensile strength using this test method is relatively high. The membranes M2, M3 and M4 exhibit relatively low tensile strengths close to or below the recommended requirement of 0.5 MPa tensile strength.

The membrane M5 was introduced as a substitute for M1 and M2. M3 was discontinued for further testing. The results for series 2 which only includes membranes M1 and M5 are shown in Fig. 32. This testing context shows that saturation through 60 days immersion of the entire slab gives a significant reduction of the tensile strength for M1 and a slight reduction of tensile strength for M5 compared to dry specimens. Eight freeze–thaw cycles to -20°C result in a reduction of tensile strength from approximately 0.7–0.5 MPa for M5. For M1 no readings were possible after the freeze–thaw cycles due to jamming of the drilling equipment at the membrane. For both membranes the

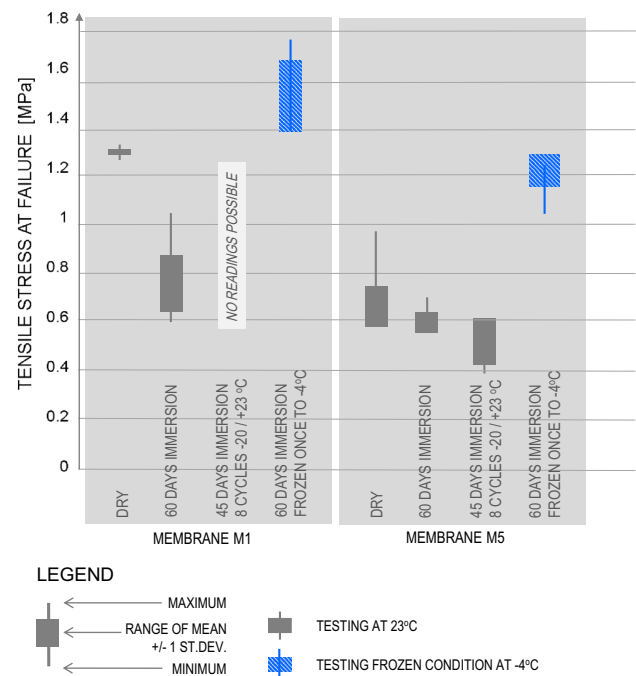


Fig. 32 Results from tensile bond tests for test series 2 (Table 15), in situ pull test method

tensile strength measured in frozen condition was significantly higher than for the measured strengths in dry or saturated condition.

Series 3 and 4 (Table 15) represent in situ readings conducted with horizontal drilling on tunnel walls in different lining sections ranging from complete tunnel to large scale lining structure in a laboratory (Fig. 7). Exposure to moisture took place through the substrate sprayed concrete. Results from the tunnel test sites exhibit high tensile strengths in the range 1.1–1.6 MPa, with 1.3 MPa as the mean value (Fig. 33, left part). Two readings could be made at a wet crack (defect) in the inner lining, at which 0.8 MPa tensile bond strength was measured. Since realistic moisture contents were achieved in the lining structure at the SINTEF freezing laboratory, the effect of cyclic freezing and thawing on tensile bond strength could be measured (Fig. 33, right part). An initial tensile bond strength of 1.4 MPa at realistic moisture content was measured. After 20 and 35 freeze–thaw cycles with -3°C minimum temperature at the membrane during each cycle, a slight reduction to respectively 1.15 and 1.1 MPa tensile strength could be measured. A tensile strength in the range of 1.1 to 1.3 MPa was measured in frozen condition at -3°C at the membrane. An additional freeze–thaw exposure with 20 cycles with a minimum temperature of -7°C at the membrane was conducted after the first 35 cycles to -3°C . Tensile strengths ranging from 0.4 to 0.7 MPa were measured after this exposure. Difficulty in

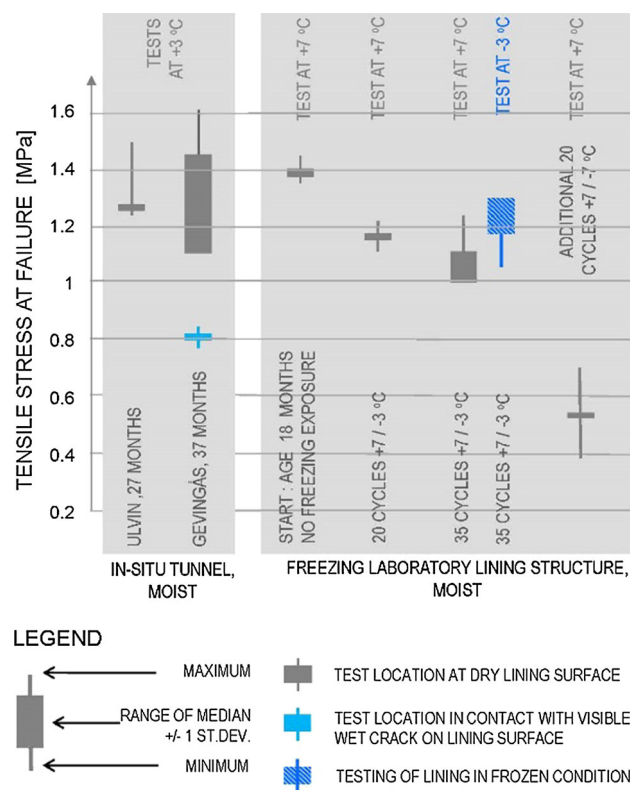


Fig. 33 Results from tensile bond tests for membrane M1, test series 3 and 4 (Table 15), in situ pull test method

conducting the pull tests was experienced during the last series at -7°C due to damage in the outer part of the concrete lining.

6.7 Microscope Analyses of the Interfaces Between Concrete and Membrane

Scanning electron microscope (SEM) analysis of the interfaces of the membrane-concrete structure was conducted on specimens obtained from slabs which had been constructed with realistic application methods of both materials. The main purpose of this analysis was to study any visual characteristics or significant differences between the two interfaces, illustrated in Fig. 34 which could be of importance for the interpretation of the tensile bond and shear strength test results.

The interface on which the membrane has been applied on the substrate concrete (interface 1), shown in Fig. 35 exhibits a sharp contrast between membrane material and concrete material. Membrane material can be seen filling the irregularities of the sprayed concrete surface. The two materials exhibit distinct phases with no visible transition zone.

The interface on which the secondary lining concrete has been applied onto the membrane (interface 2) shown in

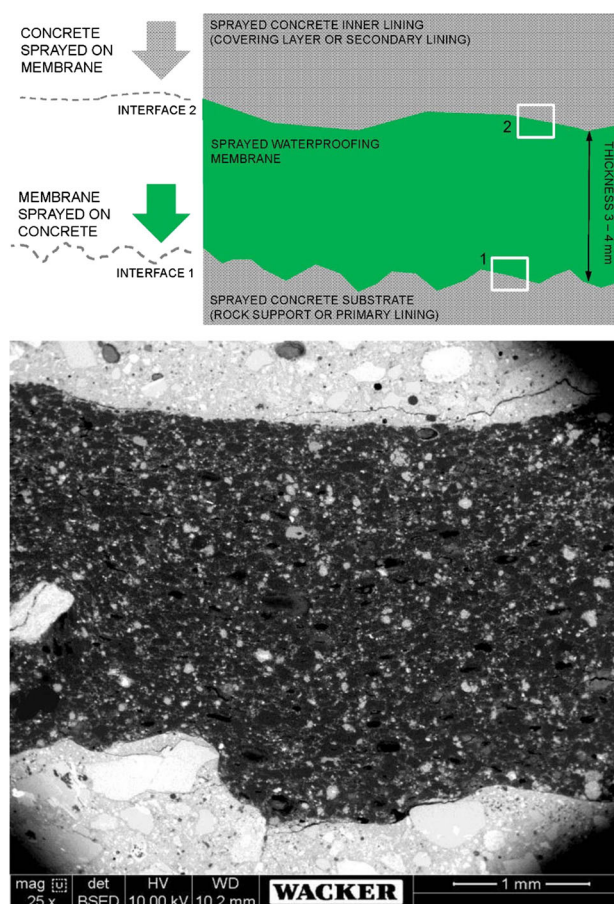


Fig. 34 Principle sketch and photo of the two interfaces between membrane and sprayed concrete. The interfaces 1 and 2 are shown respectively in Figs. 35 and 36 (courtesy by Wacker Chemie AG)

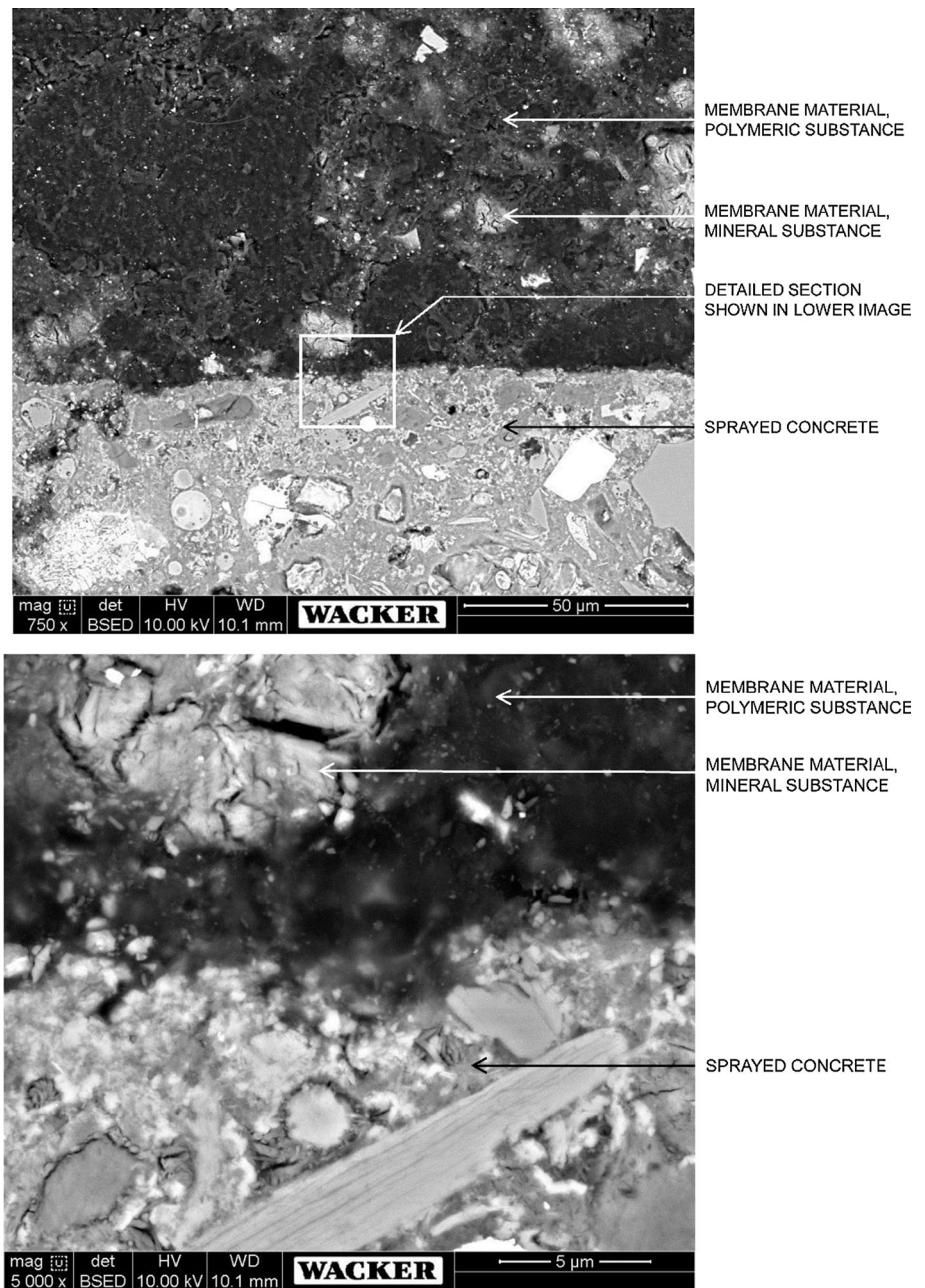
Fig. 36 exhibits a different morphology than interface 1. A transition zone of approximately $15\text{--}25\ \mu\text{m}$ thickness with visible effects of the impact of the sprayed concrete on the membrane can be clearly seen. This transition zone consists of a mineral phase with visible needle shaped crystals which separates the membrane material from the sprayed concrete material. With spectral analysis the mineral substance at the interface was found to be mainly composed of calcium carbonate CaCO_3 .

7 Discussion of Results

7.1 General

The testing of deformability and mechanical strength in this study contain accelerated or short term tests with main aim of simulating a loading scenario which takes place in the tunnel lining. The loading scenarios caused by thermally induced deformations considered in the loading

Fig. 35 Images obtained by SEM-microscopy of interface 1, with membrane spray applied onto a primary lining (rock support) sprayed concrete substrate. *Top* 750× enlargement. *Bottom* 5000× enlargement (courtesy by Wacker Chemie AG)



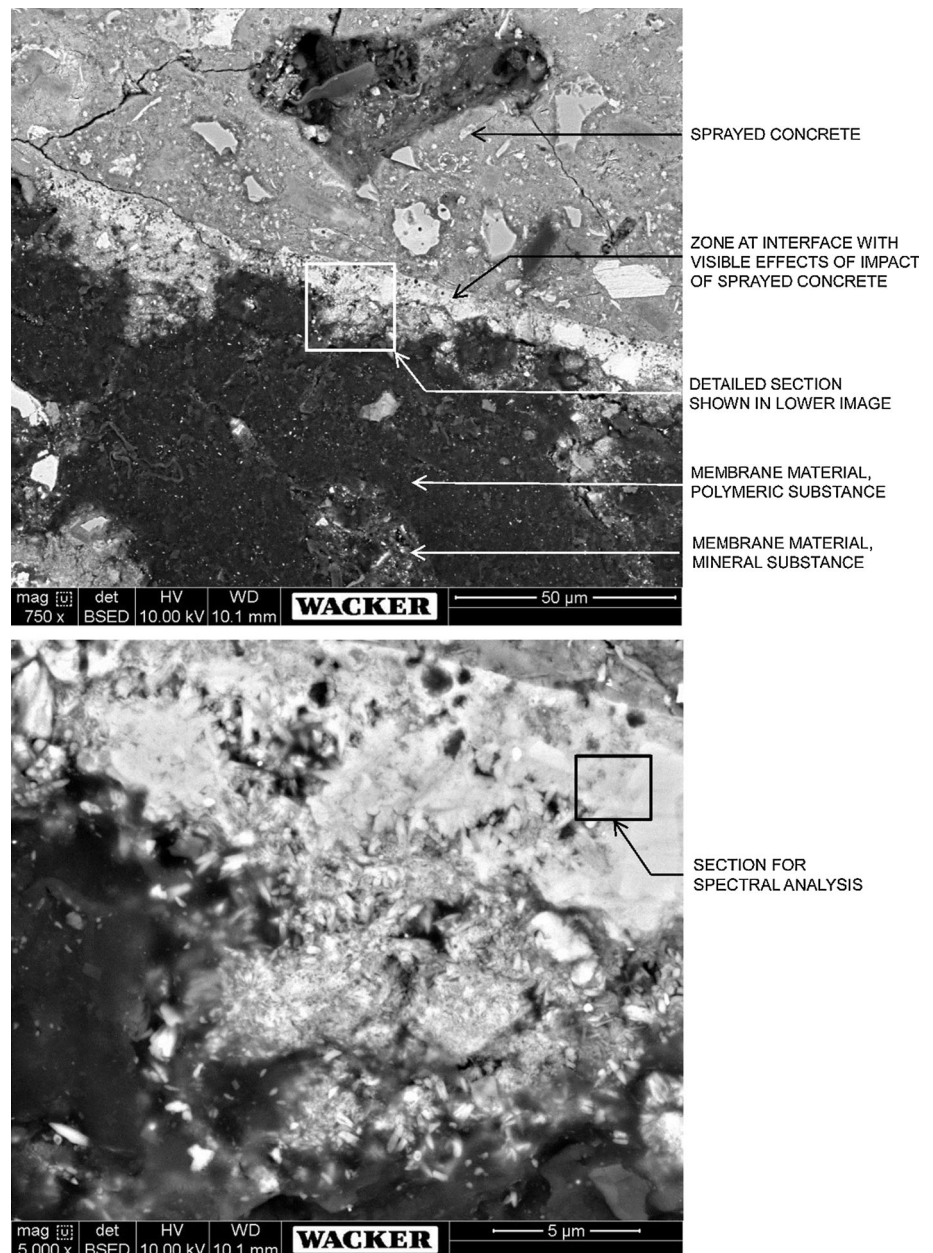
model take place over several months. Possible effects of small and very slow deformations such as healing of the material, creep or reduction of strength have not been taken into account for short term tests.

7.2 Effect of Moisture Conditions of Specimens

Establishing realistic moisture condition of specimens for laboratory testing of this category of membranes is important and difficult. A test result should always be

reported and evaluated with respect to its moisture condition. The results from in situ tensile bond strengths (with realistic moisture exposure) compared to specimens which are moisture conditioned by immersion, show that immersion very likely represents a too severe exposure to water, and gives lower strength values than realistic values. A consequence of this is that a complete testing program for membranes should include the construction of a full scale lining section in order to verify properties under realistic conditions in addition to findings from laboratory tests.

Fig. 36 Images obtained by SEM-scanning of interface 2, with sprayed concrete applied onto the sprayed membrane surface. *Top* 750× enlargement. *Bottom* 5000× enlargement (courtesy by Wacker Chemie AG)



7.3 Thermal Exposure

The measured and calculated temperature profiles in the lining structure in this study cover freezing exposure with temperatures in the tunnel air in the range of -6 to -9 °C. Such temperatures in the tunnel air will occur under severe winter climate with outside air temperatures below -10 °C over sustained periods of time (STA 2012). The rock mass temperature at shallow locations in Scandinavia is normally 6 – 8 °C. This was measured in two Swedish studies (STA 2012) as well as the measured rock temperatures at the Ulvin site (Fig. 6, Sect. 4.4), as well as in the Gevingås rail tunnel (Holter and Geving 2015). The precise air

temperature conditions at a given location in a tunnel needs to be assessed in each single case based on the local meteorological conditions and the ventilation characteristics of the tunnel.

7.4 Effect of Geometry of Specimens

The interfaces between membrane and sprayed concrete in tunnel linings exhibit surfaces with a certain degree of roughness. The measured mechanical properties shear and tensile strength will be influenced on the geometry of the interfaces which in turn will cause increased scatter. Our laboratory testing of specimens with planar surfaces

represents ideal and unfavorable geometrical conditions, and takes no account for effects of surface roughness. For the specimens prepared from slabs with lining structure, the concrete surfaces were prepared by floating in order to produce the same geometry for all specimens. Our test results obtained from specimens with planar surfaces cannot be directly translated to the in situ properties. The peak stresses obtained in the laboratory for tensile and shear testing are likely to be lower than what would be the case under realistic interface conditions regarding moisture and geometry. On the other hand, specimens with the realistic roughness of the sprayed concrete surfaces would have introduced scatter making the interpretation of the results difficult, as well as limiting the reproducibility of the tests. For the tensile strength, our in situ measurements are the most representative. Such in situ measurements should be included in a test program in order to obtain values from realistic surfaces in addition to simplified or idealized surfaces during laboratory testing.

7.5 In situ Mechanical Loading of Lining and Membrane

The construction sequence of a waterproof SCL structure normally implies that the membrane and inner lining be applied after tunnel breakthrough, or several months after excavation and construction of the primary lining. Therefore the primary lining needs to be designed to be stable and designed for any rock mechanical loads before the membrane is applied. In our study we have therefore only included loads which can be imposed to the membrane by the possible effects of the membrane itself or the inner lining sprayed concrete.

7.6 Elongation and Crack Bridging

Elongation performance of a sprayed membrane according to DIN53504 (2009) can only give an indicative figure for the required elasticity for a tunnel lining purpose. This elongation performance exhibits significantly higher sensitivity to lower temperatures compared to the crack bridging. Conclusions based only on elongation results for temperatures 0 and -3 °C would likely deem the membrane unsuitable for such thermal exposure. The crack bridging results show significant performance at freezing temperatures, although a decreasing performance at temperatures 0 °C and below is observed.

We have applied strain loads on the membrane within a range to be expected by the effects of shrinkage and thermal expansion. Thermal fluctuations from approximately -3 to 15 °C can be expected at the membrane location within the lining structure. Thermally induced crack

opening with an average crack distance of 1 m and a thermal change of 18 °C can be calculated to be in the order of 0.2 mm based on the thermal expansion coefficient. Our in situ crack measurements suggest a 0.2 mm crack opening for a drop in temperature of 6 °C. With a total thermal change over the year of approximately 18 °C in the lining structure at the membrane, 0.6 mm crack opening can be assumed. The possible shear deformations along the membrane interfaces caused by differential shrinkage or thermal expansion are in the same order of 0.5–0.6 mm. Our suggestion to use 1 mm as a crack bridging requirement and 1 mm as a critical shear deformation magnitude is therefore likely to be on the conservative side. Our crack bridging testing takes no account for any hydrostatic exposure at the cracks. We have only included the effects of high moisture content achieved by conditioning at RH 95 %.

7.7 Shear Performance

Shear testing of the membrane can contain several sources of error such as the loading rate, the normal loading mode and a possible oblique membrane plane relative to the shear direction. The applied loading rate during the test in the laboratory was 0.5 mm per minute whereas an in situ shear straining of the membrane most likely would take several months. Effects of creep and self healing therefore most likely would occur. Such effects are not accounted for in our short term test. The specimens for our tests had floated sprayed concrete substrate surfaces and were moisture conditioned by immersion. This likely represents an over-exposure to moisture compared to in situ conditions. Hence, our laboratory findings for peak shear stress and shear stiffness are likely to be lower than values in realistic moisture exposure conditions.

7.8 Tensile Bond Strength

The site testing show consistent high values for tensile bond strength (Sect. 6.6.3, Fig. 33). At testing these lining sections had a history of several thermal expansion cycles as well as the exposure to the differential shrinkage between the two concrete layers. The test results from the Ulvin site also include one complete freeze–thaw cycle to approximately -3 °C at the membrane location. The measured high values for tensile strength indicate no in situ degradation of the lining after 4 years.

The laboratory testing on core specimens possibly contains three main sources of error: the geometry of the interfaces, the moisture condition of the specimen and the alignment of the pull direction parallel to the core axis. In addition the effect of a short term test with a duration of a few minutes might fail to account for all long term effects.

Float finished concrete surfaces will normally result in a locally higher water/binder content and consequently higher porosity and possibly higher permeability. A slightly higher water exposure at the interface between membrane and concrete with a specimen with float finished surfaces compared to non-floated surfaces is therefore possible. The alignment of the pull equipment based on visual assessment will sometimes be difficult. Specimens without a perfect alignment in the testing machine might receive partial bending loads, and hence exhibit lower peak stress during the test. The in situ pull test method described in Sect. 5.3, Fig. 15, eliminates the three afore mentioned sources of error. However, with the available equipment a controlled loading speed could not be precisely applied. The effect of wet core drilling for either of the methods is unavoidable. Water exposure will soften the membrane at the core surface. When drilling in a downwards vertical direction on a slab of lining structure, the drilling water will fill the core groove and expose the membrane to water immediately before testing. When drilling horizontally in a lining structure the exposure to water will be less.

7.9 Performance Under Freeze–Thaw Exposure

Our investigations pertaining to freeze–thaw durability comprise tensile bonding strength, elongation and crack bridging. The findings from the tensile testing after freezing exposure to $-3\text{ }^{\circ}\text{C}$ indicate that no significant damage occurs at this temperature. The likely explanation for this is the unsaturated condition of the concrete and membrane materials. This allows the volumetric expansion during the freezing of water to buffer into air filled voids without creating damage. For temperatures lower than $-3\text{ }^{\circ}\text{C}$ at the membrane location, thermally insulating measures need to be considered.

7.10 Durability and Service Lifetime

Prediction of service lifetime under freezing exposure is an important question. Our testing of tensile bond strength contains accelerated freeze–thaw tests in order to simulate a slightly more severe exposure with a high number of cycles which can be related to a period of service time. The number of freeze–thaw cycles that occur per year will vary from year to year in addition to the characteristics of the location. For tensile bond we have conducted 35 cycles to $-3\text{ }^{\circ}\text{C}$ at the membrane with 48 h per cycle which resulted in only minor reduction of tensile bond strength. Effects of healing between each freeze–thaw cycle are not accounted for in such an accelerated test layout. This indicates that real exposure would be less severe than our testing, and that our findings with high tensile strength after freezing exposure is likely to be realistic, or even conservative.

Only when exposing the lining structure to 20 freezing cycles to $-7\text{ }^{\circ}\text{C}$ at the membrane location following the 35 cycles at $-3\text{ }^{\circ}\text{C}$, a significant reduction in tensile bond strength could be observed. A precise service lifetime prediction is not possible based on our results. However, when this lining system is used in tunnels with moderate freezing exposure, with a lowest temperature of $-3\text{ }^{\circ}\text{C}$ at the location of the membrane, a service life time of 100 years or more is likely.

7.11 Recommended and Planned Further Work

The time dependent effects of in situ moisture exposure will be investigated further with continued sampling and testing of moisture content as well as in situ tensile bonding strength at the test sites.

Our study includes cases with low hydrostatic pressures. The effects of higher hydrostatic pressures (more than approximately 2 bars at the interface between rock and concrete) cannot be substantiated based on our results. Further material testing and large scale model investigations verified by field testing in order to substantiate the detailed behavior at the water filled cracks which expose the membrane are required. Such testing should account for all relevant material properties.

The detailed shear load characteristics need to be investigated in further depth. The main issues are: effects of long term, slow loading, creep and the normal loading mode, as well as the normal stiffness (with respect to the membrane surface) of the secondary lining structure.

8 Conclusions

A study of the properties of sprayed membranes for SCL in hard rock has been carried out with the following main scope:

- Assessment of loading, moisture and freezing exposure conditions based on field and large scale laboratory investigations.
- Evaluation of laboratory investigation methods.
- Conducting of laboratory investigations.
- Assessment of membrane properties including performance under freeze–thaw exposure.

The main findings from this study are the following:

- The main mechanical loading mechanisms on the membrane have been found to be represented by movement over cracks in the sprayed concrete and shear straining caused by differential shrinkage and thermal expansion.

- The moisture exposure to the membrane through the interfaces with the sprayed concrete leads to an in situ moisture content corresponding to 30–40 % of the membrane's maximum water uptake potential. This has been found to be governed by the moisture properties of the membrane and concrete materials and the bonded contacts between these two materials.
- Membrane products with low polymeric content (below 70 %) exhibit low elasticity and are most likely unsuitable for tunnel waterproofing purposes in a bonded SCL context.
- Testing methods need to include details regarding moisture preconditioning and moisture exposure in order to test realistic materials and substantiate statements on in situ performance.
- A test program should include field testing in order to assess the relevance of the findings from laboratory testing.
- Testing of tensile bond strength on core or slab specimens in the laboratory which are conditioned by immersion, tend to give slightly lower measured values compared to site or large scale model testing.
- Testing of crack bridging shows decreasing performance at decreasing temperature. With 3 mm membrane thickness bridging of 1 mm crack opening at $-3\text{ }^{\circ}\text{C}$ at the location of the membrane in the lining has been found possible.
- Testing of shear properties indicate linear shear elasticity up to approximately 1 mm shear deformation.
- Testing of tensile strength show high in situ tensile bond strengths in the range of 1.1–1.5 MPa after 4 years.
- Exposure to cyclic freezing-thawing shows no significant reduction of the tensile bond strength at $-3\text{ }^{\circ}\text{C}$ at the membrane location.
- Further work is required to substantiate the performance of an SCL lining structure exposed to high hydrostatic pressures as well as effects of long term mechanical exposure.

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