19th Australasian Tunnelling Conference – Acosta-Martínez, Stewart and Hudson-Smith (Eds.)
 ISBN 978-0-85825-002-4

High temperature bond behavior of Spray Applied Waterproof Membranes (SAWMs)

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ABSTRACT: Unlike self-supporting linings like cast in situ linings with sheet membranes, composite shell or permanent concrete linings need extra support. These systems rely on the waterproofing membrane's double bonding ability to hold the sprayed membrane and inner surface of fire protection layer in place. A bond strength of 0.5 MPa at both membrane interfaces was established as the minimum industry standard (e.g. ITAtech Guidelines for SAWMs). The paper discusses the load bearing and bond behavior of three SAWMs based on ethylene-vinyl acetate copolymer (EVA) and Styrene Butadiene Rubber (SBR) technology which becomes critical in case of fire events to ensure safe access to - and structural soundness of - underground structures during and after fire events. Experimental setups were developed based on the relevant industry standards and the bond and behavior of the membranes were tested at elevated temperatures and thereafter, when the membranes were cooled back down to room temperature.

1 INTRODUCTION

Underground construction is growing worldwide because it reduces surface space consumption and keeps infrastructure protected from the various threats they might be exposed to. Whether it is for tunnels, caverns, basements or underground stations, it is essential to keep these underground structures watertight. One of the most effective ways to achieve this is the use of SAWMs, which are sprayed directly onto the surface to create a waterproof barrier.

SAWMs are popular because they are easy to apply, especially in tunnels and structures with complex shapes. The double bonding properties of SAWMs allows them to adhere to both primary and secondary linings eliminating the need for traditional cast in-situ concrete as secondary lining, which typically requires large shutters and additional manpower. This not only simplifies construction in complex tunnel geometries but enhances efficiency by using the same equipment and personnel already available on site (Dimmock, Haig & Su 2011).

Due to the confined nature of underground structures and the limitations on escape ways fire safety is always a major concern in underground structures. In double bonded systems the membrane is part of the load bearing system or even just the substrate for fire protecting layers and hence it is essential that the cohesive and adhesive strength of the SAWM is not compromised during or after underground fire events to the extent that parts of the structure de-bond and pose threats to first responders or during rehabilitation work. In the event of fire, temperatures can reach very high levels which, due to their polymeric nature, can weaken the membrane and its bond to neighboring layers of the structure.

According to ITAtech guidelines, a minimum bond strength of 0.5MPa is recommended for both membrane interfaces to ensure structural soundness, safety and durability, (ITAtech Activity Group lining and waterproofing 2013). The ISO 834 fire curve is a widely used standard for structural fire testing, representing temperature development under severe fire conditions (International Organization for Standardization, 2025). In real tunnel environments, sprayed waterproofing membranes are not directly exposed to fire. They are typically embedded between concrete layers, and the use of fire protective layer which is common industry practice further reduces the thermal exposure. As a result, the temperature experienced by the membrane is significantly lower than the surface temperature during a fire. A large-scale fire test by Duan et al. (2021) showed that at depths of approximately 30 mm and 60 mm within concrete, temperatures after 120 minutes of fire exposure ranged from 100 °C to 160 °C, depending on the location across the tunnel section (Duan et al., 2021). This indicates that the membrane experiences much lower temperatures than the temperature mentioned in the ISO 834 curve. In practice, a 50 mm concrete protective layer is commonly applied over the membrane. Based on all this information, in this study the performance of three different SAWM products were assessed under heat exposure of 100°C and 160°C.

Membranes 1 and 3 are powdered products based on EVA polymers and membrane 2 is a liquid SAWM based on SBR technology. The study aimed to evaluate the properties such as load bearing behavior, bond and cohesive strength of spray applied waterproofing membranes under elevated temperature conditions as well as its form stability when sandwiched in between two concrete layers.

2 OBJECTIVES

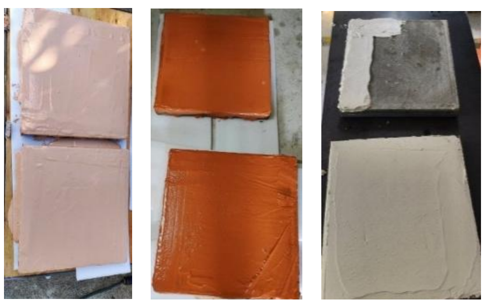
The main objectives of this study are:
1. The evaluation of the bond strength of three different spray-applied waterproofing membranes under elevated temperature conditions.
2. The assessment of stability and performance of the SAWMs in a sandwiched, confined application, embedded between two layers of concrete under elevated temperature conditions.

3 METHODS

3.1 *Double-bond strength evaluation under elevated temperatures.*

To address the first objective, a modified version of ASTM C1583/C1583M was developed (ASTM International,2020). The method described in the standard presents two major practical challenges: Firstly, core drilling through the secondary lining and the membrane bears the danger of breaking the bond between concrete and membrane due to vibration, and secondly, glue failure (cohesive or adhesive) is a quite regular occurrence, especially when applied onto water-based membranes. For the here determined high-temperature application this issue is particularly prominent in addition to the property changes of the glue at higher temperatures.
To overcome these limitations, a following tailored test setup was devised:
- Substrate Preparation: Commercially available concrete pavers (l x w x h: 400 mm x 400 mm x 40 mm) were used as the substrate. Each paver was coated with two or more layers of membrane, adding up to a 3 mm dry film thickness.
- In figure 2, membrane 1 (left) and membrane 3 (right) are powdered materials and EVA based whereas membrane 2 (middle) is a liquid SBR polymer-based product.

Figure 1. Concrete Pavers.



Figures 2a, 2b and 2c. Concrete Pavers coated with 3mm thick membranes 1, 2 and 3.

- Casting individual pull-off specimens onto the membranes: Cylindrical cement mortar specimens (50 mm diameter, 50 mm height) were cast directly onto the membrane surfaces, eliminating the need for core extraction. Thermocouples and M10 threaded bolts were embedded within the mortar during casting.

Figure 3. Cylinder mold with thermo- couple

Figure 4. Threated bolt centralized in casting lid

Figure 5. Cylindrical specimens cast and covered for curing

- Load application system: The bolt served as a mechanical anchor for a custom-fabricated dolly, enabling the direct connection to the pull off tester without the use of adhesives.

Figure 6: Load Application System

Figure 7. Sample slabs inside the oven

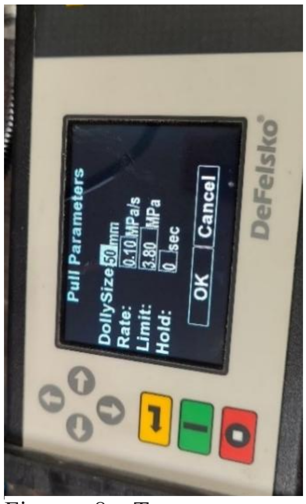


Figure 8. Test parameters, displayed on pull-off tester screen

- Temperature control and monitoring: Prior to testing, the samples assembled were subjected to elevated temperatures (100°C and 160°C) in a laboratory oven. Thermocouples embedded in the cement mortar measured internal temperature and overnight heating continued until a stable temperature was reached.
- Testing: The membrane was cut around the cast specimens. Pull off tests were conducted at room temperature on some specimens to verify the test method and set the reference. The membrane and specimen carrying concrete slabs were placed inside an electric oven and heated overnight. After heating to the desired temperatures, the concrete slabs were taken out of the oven and specimens were immediately pulled off, recording the actual pull-off temperature and bond-strength. Finally, the samples were cooled back down to room temperature and the remaining specimens were pulled off recording the bond strength after the simulated fire events.

3.2 *Performance evaluation under confined / sandwiched conditions*

The second objective was an additional test resulting from an observation during experimental campaign one. During the first stage of experiments the formulation of bubbles underneath the membrane was observed in areas where it was exposed directly without any mortar cast onto it. In order to address this experimental artifact and to simulate confined site conditions during a fire event, specimens were prepared where the membrane was sandwiched between two concrete layers and heat exposure occurred from only one side.

Figure 9: Thermocouple 1, 2 and 3 placed from corner to center of paver

Figure 10: Thermocouple 4 elevated and placed in center of mortar layer

Figure 11: Sprayed membrane sandwiched between concrete paver and cement mortar layer

In actual underground fires, the heat typically flows from the interior side, affecting the protective layer first, while the outer surface which is in contact with the surrounding ground remains at a lower temperature.

To simulate this scenario, a wooden frame was constructed in the shape of the oven door. This setup allowed the protective mortar layer of the specimen to be placed inside the oven, while the concrete paver side remained outside at room temperature. The experiment setup created a one directional heat flow, replicating the thermal conditions that may occur during underground fires. For all three membranes the temperature of the oven was set at 210°C and the oven was turned off when at least two of the thermocouples reached around 160°C.

Figure 12: appr. 50mm thick mortar layer on membrane

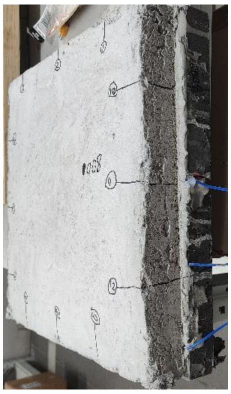


Figure 13: sandwiched membrane

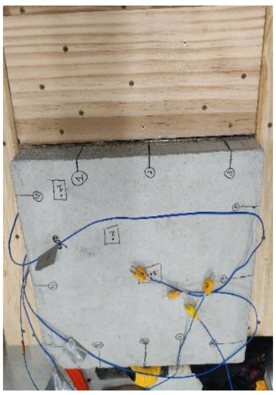


Figure 14: specimen prepared for heat exposure

Figure 15: specimen placed for heat exposure

After the specimens cooled down to room temperature the thickness change of the sandwich structure was measured to determine the volume stability of the membrane under heat exposure.

Also, cores were drilled from the surface using diamond core drill through the previously thermally stressed membrane into the substrate and double bonding performance on the sandwich structure was determined by means of pull-off testing.

4 RESULTS

4.1 *Bond strength results at elevated temperatures*

Initial tests were conducted at room temperature to verify the effectiveness of the modified pull off test setup and set the bond strength baseline for all three SAWMs. All three materials demonstrated pull off strengths exceeding the minimum industry benchmark of 0.5 MPa. This confirmed that the test method was valid for further evaluation at elevated temperatures.
Subsequently, pull off tests were conducted at two elevated temperatures: 100°C and 160°C. After each thermal exposure, the specimens were cooled back to room temperature, and the pull off tests were repeated to assess bond strength. Thermocouples embedded in the mortar confirmed the internal temperature of the specimen during each test.

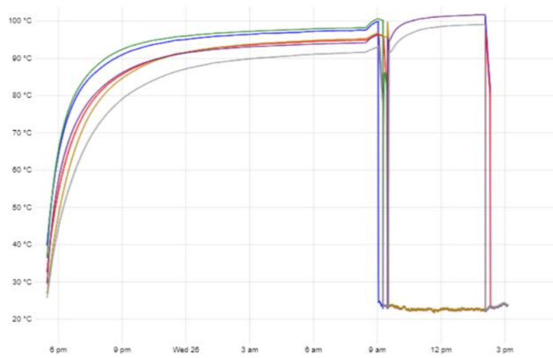


Figure 16. Temperatures recorded within specimens during heat exposure at 100 ° C

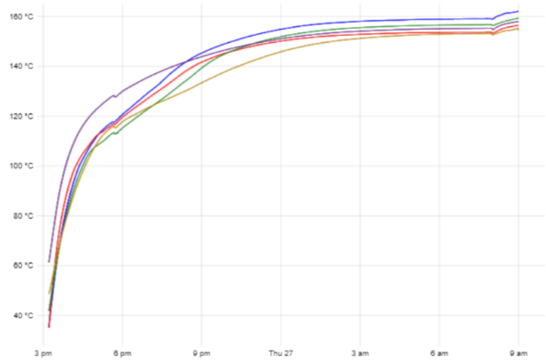


Figure 17. Temperatures recorded within specimens during heat exposure at 160 ° C

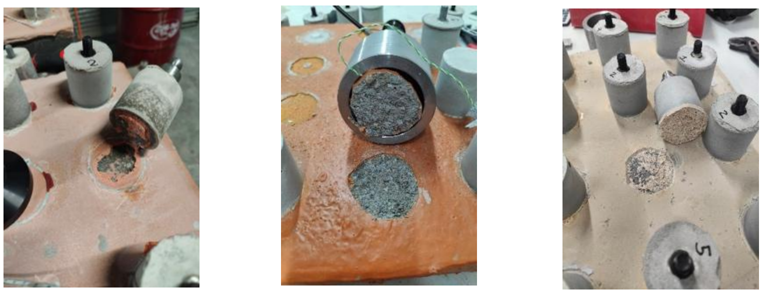


Figure 18 a-c: all possible failure modes were observed while pulling off the specimens from the membranes (cohesive failure in substrate, membrane or cast on mortar specimens, adhesive failure at interface either side of the membranes as well as mixed failure modes)

Table 1. Pull-off test results for membrane 1 (EVA)

Test Condition	Average bond Strength (MPa)	Average Specimen Temperature at Pull-Off (°C)
Reference test at 23°C	1.02	23
Exposure to 100°C	0.28	90
After exposure to 100°C	1.07	23
Exposure to 160°C	0.04	147
After exposure to 160°C	0.45	22

The EVA based membrane 1 exhibited a strong bond at room temperature during the virgin reference test as well as after exposure to 100ºC and 160ºC. Expectedly the bond strength dropped significantly while heated, especially at 160°C as the elongation behavior of EVA polymers increases with temperature. The heat exposure of the substrate resulted however in water vapor developing which created partial de-bonding of the membrane. The low results for exposure to 160ºC and afterwards can also be partially attributed to this effect.

Table 2. Pull-off test results for membrane 2 (SBR)

Test Condition	Average Bond Strength (MPa)	Average Specimen Temperature at Pull-Off (°C)
Reference test at 23°C	1.34	23
Exposure to 100°C	0.38	90
After exposure to 100°C	1.05	20
Exposure to 160°C	0.14	134
After exposure to 160°C	1.37	22

Membrane 2 showed good thermal resistance, maintaining relatively high pull off strength values across all stages. The bond strength at elevated temperatures is lower than 0.5 MPa but still within a range to prevent secondary lining dropouts. After cooling from 160°C, the bond strength slightly increased compared to initial reference value which may indicate the hardening of the membrane or simply increased bonding forces between the membrane and both concrete layers.

Table 3. Pull-off test results for membrane 3 (EVA)

Test Condition	Average Bond Strength (MPa)	Average Specimen Temperature at Pull-Off (°C)
Reference test at 23°C	0.94	23
Exposure to 100°C	0.21	91
After exposure to 100°C	0.83	23
Exposure to 160°C	0.26	149
After cooling from 160°C	1.20	22

Similar to membrane 2, membrane 3 also showed a reduction in bond strength during heating phases but recovered well after cooling. The post cooling pull-off strength values were close to or higher than the virgin reference.

4.2 *Results on sandwich system*

For the second test setup, the thickness of the sandwich structure was measured at 12 marked points using a vernier caliper before heating. After thermal exposure, thickness was measured again at the same points to access for any deformation. Across all three membranes, minor surface cracks were observed around the membrane area, but no visible blistering occurred. The overall sandwich structure remained intact, and the protective layer and concrete paver stayed well bonded to the membrane.

Table 4: Thickness change after exposure to 160°C

Description	Membrane 1 (EVA)	Membrane 2(SBR)	Membrane 3(EVA)
Average thickness before test (mm)	94.0	88.6	93.9
Average thickness change (mm)	1.2	1.0	0.7

Even though the membrane thickness was not measured exactly, it must be stated that with a thickness increase of around 1 mm over an average membrane thickness of around 3 mm indicates that some sort of change must have happened within the membrane or the concrete-membrane interfaces.

After the samples were cooled from 160°C to room temperature, cores were drilled through the cement mortar, simulating the secondary lining and through the membrane into the concrete paver. Dollies were glued onto the core surface and pull off tests were conducted.

Figure 19: Pull off test – adhesion failure to secondary lining

Figure 20: Sandwich specimen after heating at 160°C

Figure 21: Pull-off tests

Table 5: Average pull-off double-bond strength after exposure to 160ºC

Description	Membrane 1(EVA)	Membrane 2 (SBR)	Membrane 3(EVA)
Number of cores	3	3	3
Failure mode	Adhesion to cement mortar	Adhesion to cement mortar	Adhesion to cement mortar
Average pull-off strength (MPa)	0.27	0.38	0.27

It must be stated that the pull off strength results stated in table 5 were considerably lower as compared to results from the first test campaign (method 3.1). This may be due to the use of a diamond core drill during sample preparation. The high-speed drilling, associated vibrations may have caused damage to the bonded surface, raising concerns about drilling method and its potential impact on bond strength. The observed failure mode, for all cores to fail at the interface membrane – cement mortar (secondary lining) is strongly supporting this theory.

In order to determine whether the low bond strength recorded is indeed an artifact of sample preparation or is credited to thermal damage to the bonding ability, further testing is recommended avoiding core drilling after thermal exposure.

5 CONCLUSION

Based on the findings of the study it can be concluded that the tested EVA and SBR polymer based SAWM products remain mechanically intact during and after underground fire events for assumed membrane temperatures of 100ºC and 160ºC. Other properties such as water tightness or durability after fire events were not considered.

For the duration of the increased membrane temperature its load bearing behavior is reduced and after the cool down period returns to its original or even increased values. This reduced load bearing ability remains at all times at a level where no dropouts from secondary lining or fire protecting layers based on membrane failure would be expected. Based on these findings, the use of the tested products does not add any additional risk to first responders or during remedial work.

6 RECOMMENDATION

Full scale fire testing may be required based on specific project conditions and the positioning of the membrane, as performance can vary depending on design factors. Furthermore, the apparent increase in bond strength observed in membrane 2 after cooling warrants further investigation to understand its nature and effects. For sandwich system, it is also recommended to employ testing methods that eliminate the need for drilling after thermal exposure, as drilling may compromise the accuracy of bond strength measurements.

7 REFERENCES

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