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# Performance of Synthetic Sheet Waterproofing Membranes Sprayed with Steel Fiber-Reinforced Shotcrete

## Testing for Waterproofing Membrane Integrity After Spraying

By Antoine Gagnon, Marc Jolin, and Jean-Daniel Lemay

The recent Position Statement #2, “Spraying Shotcrete on Synthetic Sheet Waterproofing Membranes,” published by the ASA Underground Committee, pointed out many aspects critical to successful performance and raised some potential issues affecting the placement.<sup>1</sup> In the position statement, specific techniques are presented to prevent problems such as delamination, voids, or fallouts. In the discussion, the potential issue of steel fiber-reinforced shotcrete (FRS) causing damage and potentially puncturing the membrane was raised. From the experience of the committee and the available information, it was concluded that:

- The forces acting on the fiber are not strong enough to push the fiber into the membrane; and
- The fibers tend to orient parallel to the membrane on impact, thus reducing the risk of damage.

In parallel, a research project on this subject had been undertaken at Université Laval’s Shotcrete Laboratory, with the results only recently available. This article presents the results of this investigation.<sup>2</sup> It is intended to support ideas presented in the ASA position paper and to help in the decision-making process when dealing with waterproofing membranes and FRS in underground projects.

### RESEARCH PROJECT

The research project is aimed at evaluating the potential damage and performance reduction of synthetic sheet waterproofing membrane when using steel fiber-reinforced shotcrete. The main goal is to evaluate the watertightness of a waterproofing membrane when used with steel fiber-reinforced shotcrete placement. For this project, the conditions and materials used in an actual tunneling project in New York, NY, were reproduced as closely as possible in the laboratory.

The shotcreting operation and final composite included:

- A synthetic sheet waterproofing membrane applied on an FRS initial lining with two different surface finishes; and

- Subsequent FRS sprayed onto the membranes from each surface condition.

The integrity of the membrane in the final composite panel was then evaluated with two tests:

- An airtightness test; and
- A tensile strength test.

The airtightness test was used to evaluate the watertightness of the membrane. The test method and setup were adapted from previous research and implemented in Université Laval’s Shotcrete Laboratory specifically for this project.<sup>3</sup> The tensile strength test was adapted from different membrane test standards. It was used to evaluate the behavior and maximum tensile strength of the membrane in its final state. Both tests are described with more details in the next sections.

### METHODOLOGY AND MATERIALS

The shotcrete placement in this project follows the guidelines of ACI 506R-16, “Guide to Shotcrete.”<sup>4</sup> The typical techniques and equipment used in similar research projects at Université Laval’s Shotcrete Laboratory were used. Details on the methodology and materials are presented in the following sections.

#### Shotcreting Equipment

All the shotcreting operations in this project were conducted using the dry-mix process with an Aliva 246 gun, a 1.5 in. (38 mm) diameter hose, and a hydromix nozzle.

#### Shotcrete Mixture

To subject the membrane to real-life shotcreting conditions, a mixture similar to the one employed on the New York tunneling project was used in this project. The prebagged shotcrete mixture was manufactured by King Shotcrete Solutions. Table 1 presents an overall description of the mixture design. In this case, only the use of accelerator

was omitted to facilitate overall finishing and cleaning operations. It is believed that the absence of accelerator would not significantly change the conclusions of this research. The steel fiber used was Dramix 3D provided by Bekaert Underground Solutions. The fibers were added to the shotcrete mixture during the mixing operation.

The synthetic sheet waterproofing membrane used in this project is the Mapeplan TU 20 provided by Mapei Underground Technology Team. It is a 0.08 in. (2 mm) thick polyvinyl chloride (PVC) membrane with a reported maximal tensile strength of 2175 psi (15 MPa) and maximum elongation of 250% at rupture. For this project, four sheets of membrane were used, each one measuring 20 x 20 in. (500 x 500 mm).

### Production of Test Panels

The overall purpose of this project was to create a system that would closely represent the conditions of a membrane used underground with steel fiber-reinforced shotcrete.

The first step had two FRS substrate panels sprayed to replicate an initial lining. Both were sprayed at a dry consistency, with a relatively low water content in the dry-mix shotcrete. In the mining and tunneling industry, dry-mix shotcrete is usually sprayed with a dry consistency compared to typical mixtures in the repair industry. Both substrate panels were 24 x 24 in. (600 x 600 mm) wide and 4 in. (100 mm) thick.

Each panel received a different surface finish. For the first panel (Substrate 1), the surface was screeded. It was decided to screed the surface of one panel because screeding FRS tends to expose fibers on the surface (Fig. 1(a)). This was considered a harsh condition for the waterproofing membrane. The surface of the second panel (Substrate 2), was finished with a technique often referred to as a flash finish (Fig. 1(b)). In this operation, once the desired thickness is reached, the nozzleman moves the nozzle away from the surface to obtain a more uniform and smoother surface. Also, most fibers tend to be embedded within the shotcrete. Flash finishes are very common in the industry.

Figure 2 shows the shotcrete testing area after spraying of the panels. The panels were cured for 7 days in a fog room (73°F [23°C] and 100% RH) and then kept at room temperature and humidity (approximately 70°F [21°C] and 40% RH).

After producing the initial substrate panels, the next step was placing the synthetic sheet waterproofing membrane. The membrane was applied onto the substrate panels and fixed in place using a wooden frame. This frame served two purposes:

- It kept the membrane in place while the subsequent FRS layer was applied; and
- It acted as a bond breaker between the edges of the membrane and the fresh shotcrete.

In the setup used, a 2 in. (50 mm) strip around the edges of the membrane was covered with plywood, thus protecting the membrane from the impact of fresh FRS. The section of

**Table 1: Mixture Design of Steel Fiber-Reinforced Shotcrete**

Ingredients	Description
Binders	Portland cement and silica fume
Aggregates	Follow ACI 506 Gradation #2
Fibers	Bekaert Dramix 3D 93 lb/yd <sup>3</sup> (55 kg/m <sup>3</sup> ) (theoretical)
Admixtures	None

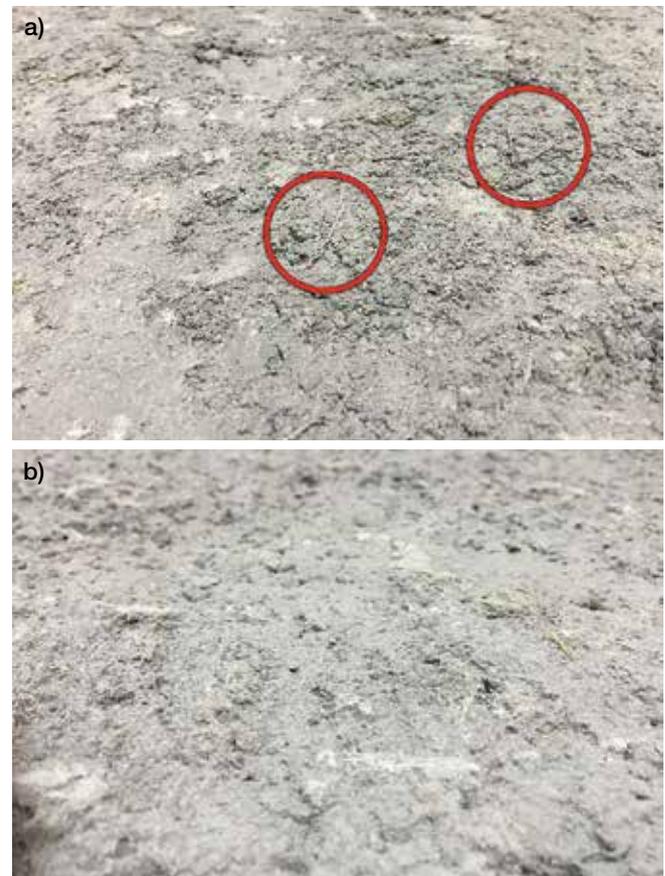


Fig. 1: (a) Close view of screeded finish with apparent fibers; and (b) flash finish with no apparent fiber



Fig. 2: Substrate panels after spraying

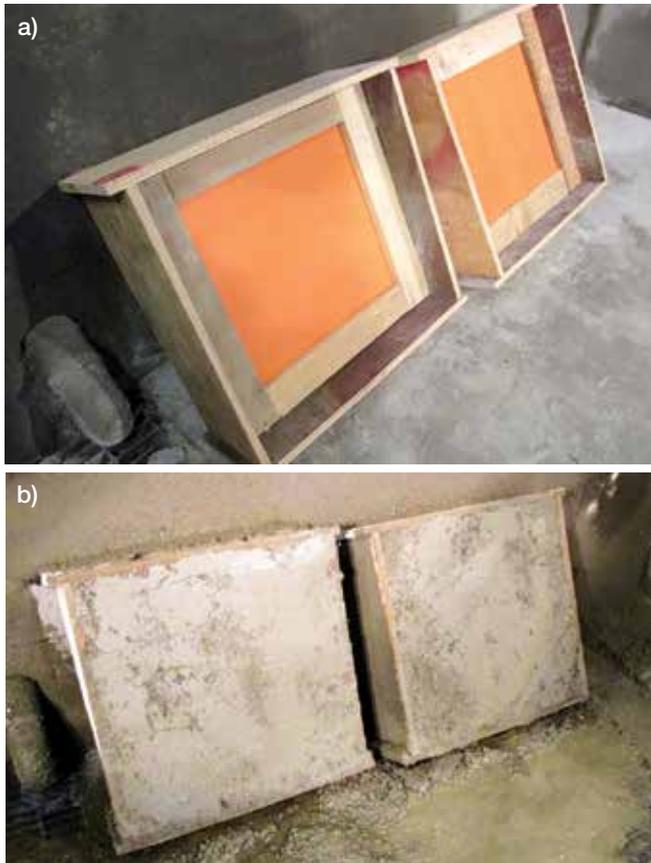


Fig. 3: (a) Substrate panels before; and (b) after second layer of FRS was applied



Fig. 4: Composite panels under loading frame

the membrane exposed to the spraying had dimensions of 16 x 16 in. (400 x 400 mm).

The final step in sample production was shotcreting the second layer. The second layer was shotcreted the same as the first layer. Figure 3 shows the setup before spraying and the composite panel after spraying. The composite panels were cured for another 7 days in the fog room (73°F and 100% RH) and then kept at room temperature and humidity (approximately 70°F and 40% RH).

After the second curing period, the two composite panels were placed in a hydraulic press to apply a pressure of 1.5 bar (22 psi). The pressure was maintained for 10 hours to simulate a pressure that would typically occur in underground applications. To ensure uniform contact between the panels, sand and plywood were placed between the panels to fill gaps. Figure 4 shows the composite panels under load in the loading frame (note that some of the panels in the picture could not be used).

Once removed from the hydraulic press, the composite panels were separated, and the waterproofing membranes carefully removed.

### Airtightness Test

One of the goals of this project was to verify the synthetic sheet waterproofing membrane can retain its waterproofing ability after being applied onto FRS and subsequently sprayed with FRS. To evaluate this aspect, pressurized air was applied on the membrane specimens taken from the composite panels. The specimens were attached to a sealed steel frame connected to an air hose. Figure 5 shows the testing frame from the membrane side and from the air input side.



Fig. 5: (a) Testing frame from membrane side; and (b) from air input side



Fig. 6: Overall view of a membrane at the beginning of the test

Five holes on each side of the frame were drilled through the membrane to allow for bolts to go through and seal the frame. The contact surface on the outside edge of the frame was aligned with the protected section of the membrane (where the 2 in. wood strips were during the second shotcreting operation). The pressurized air was injected through a hose and a regulator. The pressure was maintained at approximately 50 psi (3.45 bar) for a few minutes to allow for observation.

Though a decrease of pressure could have been measured, the reported results from this test are completely qualitative. The membrane was thoroughly inspected for perforations or any unusual deformations (for example,

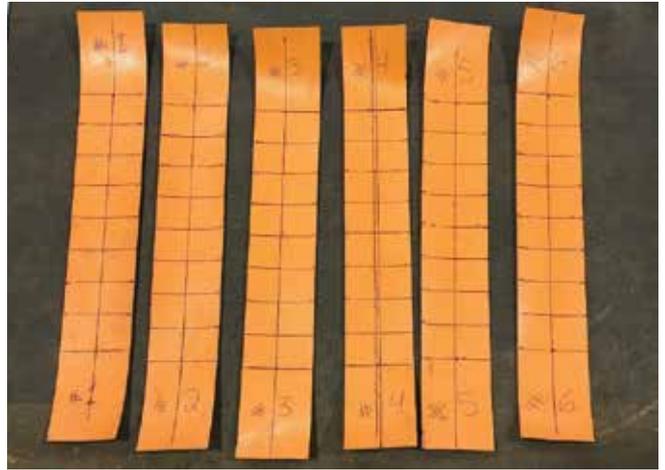


Fig. 7: Waterproofing membrane in strips before testing

bubbles, localized deformations, and tears) that may have appeared while the membrane was pressurized.

### Tensile Strength Test

The second test evaluated the impact of steel FRS on the physical properties of the waterproofing membrane. In this test, strips of the membranes were cut and loaded in tension until they either broke or the maximum displacement of the testing frame was reached. Figure 6 presents the test setup.

The tensile specimens were cut in strips of 2 in. wide by 11 in. (280 mm) long (Fig. 7). Each end of the specimen had 2.5 in. (64 mm) inside the grip, leaving 6 in. (150 mm) in the middle section. In preparation for testing, six specimens (control) were used to validate the setup, the specimen dimensions, and the general behavior of the membrane during the test. Table 2 presents the testing conditions for each specimen.

Because none of the waterproofing membranes were punctured by FRS during the creation and dismantling of the panels, it was decided to evaluate the potential reduction in strength if a hypothetical fiber was to puncture a membrane. To simulate a fiber puncturing the membrane and the effect on the membrane's properties, unsprayed specimens D-1 and D-2 had defects deliberately created using a 1/16 in. (1.6 mm) diameter drill bit. A single hole was made and placed in the middle of the membrane.

### RESULTS

The following sections present a combination of qualitative observations and quantitative measures obtained through the shotcreting operation and testing process.

Table 2: Testing Conditions For Membrane Specimens For Tensile Strength Test

Identification	Membrane condition	Defects
U-1 and U-2	Unsprayed membrane	—
S1-1 and S1-2	Sprayed on substrate I	None*
S2-1 and S2-2	Sprayed on substrate II	None*
D-1 and D-2	Unsprayed membrane	Artificial defect

\*Based on observations during airtightness test (results presented in this article)

## Visual Inspection

After taking apart the composite specimens, the shotcrete surfaces of the second layer—the one that was sprayed onto the membrane—all presented similar aspects:

- A smooth surface;
- No visible fibers or aggregate; and
- A “purplish” color (probably a discoloration from the membrane).

This agrees with general shotcreting experience and observations. As the shotcrete hits a hard substrate, it must first create a paste bed before aggregates and fibers can stick to the surface and start embedding in the shotcrete. This is substantiated by the fact that rebound is always higher in the first few millimeters of shotcrete placement on a hard substrate. Also, fibers in FRS tend to orient in a plane parallel to the receiving surface upon impact. Finally, the kinetic energy of a fiber and its surrounding shotcrete material does not appear to be high enough to push the fiber into the membrane. These observations suggest that none of the fibers from the second layer were in contact with the membrane. Figure 8 presents a close view of the smooth shotcrete surface.

There was no visible damage on the membrane from either of the finishes of Substrate 1 or 2. There was no visible dust or wear on the surface exposed to the second



Fig. 8: Closeup view of shotcrete layer sprayed onto waterproofing membrane



Fig. 9: Inflated membrane at 50 psi of air pressure

layer shotcrete placement. On the side of the membrane in contact with the first layer, dust and small indentations of aggregate were visible. Most of the dust could easily be swept away by simply wiping a glove on the surface. The difference in the finish between Substrate 1 and 2 (screeded and flash finish) did not influence the integrity of the membrane.

## Airtightness Test

None of the waterproofing membranes from either Substrate 1 or 2 showed any sign of air leakage during the airtightness test. Specimens from both substrates seemed to have similar deformation at the maximum test air pressure. For all specimens, the membrane first started inflating as the air started entering the chamber (refer to Fig. 9). Once the membrane’s maximum deformation was reached, the pressure started rising and was maintained at 50 psi.

## Tensile Strength Test

The tensile strength test was conducted on an electromechanical testing system that allows for large displacements. Despite the large displacement capacity, the limit of the frame was reached with some specimens and the test had to be stopped. This displacement was equivalent to a deformation of approximately 370% for a 6 in. long specimen. Therefore, specimens could either rupture or reach the testing frame displacement limit in this test.

Table 3 presents the maximum load, the maximum deformation, and the criterion reached to stop the test for all specimens. The deformation was calculated using the crosshead displacement and the specimen length between the clamping jaws (6 in.).

Note that the deformation presented in Table 3 is for comparative purposes only. Unfortunately, the clamping jaws used in this test could not hold the membrane specimen completely, thus it partially slipped at large deformations. In Fig. 10, the circled line was initially aligned with the upper edge of the clamping jaw. This shows that part of the specimen initially inside the clamping jaw was stretched and pulled out from the jaw. This explains why the deformations presented in Table 3 are much larger than the maximum deformation specification in the synthetic sheet waterproofing membrane technical datasheet (250%).

Though the maximum deformation presented cannot be directly used to determine the true ultimate deformation at rupture, the test results still allow for a comparison between the different membrane conditions.

A specimen from the sprayed membranes group (S2-1) ruptured before reaching the maximum displacement, seemingly presenting a different behavior from the other samples from the shotcreted panels. However, it should be noted that the failure occurred in the portion of the specimen between the clamping jaws. Thus, it is most likely caused by a strain concentration from uneven pressure inside the clamping jaws. The behavior of Specimen S2-1 is more similar to the behavior of the sprayed and unsprayed membranes than it is to the behavior of unsprayed membranes with artificial defects.

**Table 3: Results From Tensile Strength Test**

Identification	Membrane condition	Maximum load, N	Maximum deformation, %	Stopping criterion
U-1	Unsprayed	(>) 1350	376	Frame limit
U-2	Unsprayed	(>) 1241	378	Frame limit
S1-1	Sprayed on Substrate 1	(>) 1456	372	Frame limit
S1-2	Sprayed on Substrate 1	(>) 1405	376	Frame limit
S2-1	Sprayed on Substrate 2	1213	369	Membrane rupture
S2-2	Sprayed on Substrate 2	(>) 1225	376	Frame limit
D-1	Unsprayed with artificial defect	1062	273	Membrane rupture
D-2	Unsprayed with artificial defect	1070	268	Membrane rupture

The tensile results show that the presence of a defect significantly reduces the maximum deformation at the end of the test (refer to D-1 and D-2). Figure 11 shows that even a small defect in the membrane ultimately leads to the premature rupture of the membrane.

### CONCLUSIONS

The objective of this research project was to evaluate the effect of steel FRS with an embedded synthetic sheet waterproofing membrane on the watertightness of the membrane and its performance. The results show that neither the surface condition of the initial lining of FRS under the membrane nor a final lining sprayed onto the membrane affected its integrity or performance. In the air tightness test, the air pressure was maintained by the membrane after installation within the composite panel, suggesting it would remain watertight in service. Also, the specimens in the tensile strength test maintained their physical properties except when a hypothetical puncture was simulated.

The manipulation and installation of the membrane is, in the authors' opinion, much more critical than the effect of an initial or final FRS lining in contact with the membrane. For example, anchors are likely more of an issue in terms of watertightness and membrane integrity than FRS. Because of the accumulation of paste due to initial increased rebound before fiber retention, the orientation of fibers and their inability to penetrate the membrane upon impact, fibers are typically not in direct contact with the membrane when a second layer of FRS is sprayed onto the membrane. Finally, the surface finish of an initial FRS layer that subsequently has a waterproofing membrane applied onto it does not appear to influence the integrity of the membrane. In the authors' opinion, neither aggregates nor fibers in FRS seem to be an issue when in contact with such waterproofing membrane.

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Fig. 10: Membrane slipping outside the clamping jaw for crosshead displacement of 14 in. (350 mm)

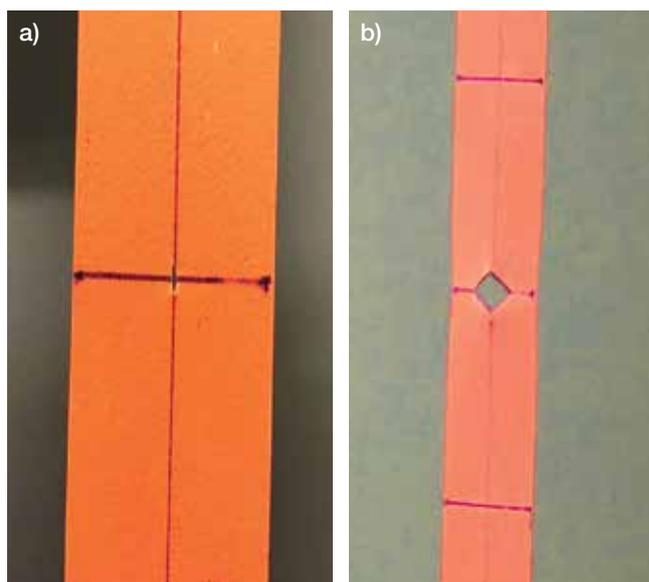


Fig. 11: (a) Specimen D-1 (artificial defect) with crosshead displacement of 9.6 in. (244 mm); and (b) displacement of 16.1 in. (410 mm). The original dimension of the hole was 1/16 in.

led the project and coauthored the initial report, is greatly acknowledged. The authors would also like to acknowledge the financial support and collaboration of Bekaert Underground Solutions, Mapei Underground Technology Team, King Shotcrete Solutions, the American Shotcrete Association, Natural Sciences and Engineering Research Council of Canada (NSERC), Fonds de Recherche du Québec – Nature et Technologies (FRQNT), Programme de Bourses de Leadership et Développement Durable de l'Université Laval, and the Fondation Famille Choquette. The exceptional technical support of Mathieu Thomassin-Mailhot, research engineer, and René Malo, senior technician, of the Department of Civil and Water Engineering at Université Laval is greatly acknowledged.

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