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A new waterproofing membrane for tailings ponds

G Spagnoli *BASF Construction Solutions GmbH, Germany*

F Clement *BASF Belgium Coordination Center, Belgium*

BZ Dilnesa *BASF Schweiz AG, Switzerland*

FH Cao *BASF BACC, China*

P Feng *BASF BACC, China*

Abstract

Tailings are the materials left over after the process of separating the valuable fraction of ore from the gangue. Tailings ponds are engineered structures created using dams, berms and natural features such as valleys, hillsides or depressions. The pumping of tailings slurry into a pond allows the sedimentation of solids from the water. Tailings ponds can be highly toxic because they are used to store harmful waste made from separating minerals from rocks or the slurry produced from tar sands mining. To minimise contamination of underlying groundwater, high-density polyethylene (HDPE) liners are used. These liners are prefabricated sheets that are welded onsite to form a continuous waterproofing membrane that prevents the migration of contaminated water into the environment. Despite their widespread application, HDPE liners have inherent performance limitations, such as leakages at the location of welds, UV resistance, maintenance and repair. This paper considers a new type of sprayable reactive membrane as a waterproofing structure. Permeability tests with the Rowe cell, chemical and durability tests (interaction with water and leachates at different temperatures, oxidation and UV resistance tests) and mechanical tests (tensile strength tests, elongation tests, puncture tests) were performed and compared with conventional HDPE membranes for tailing ponds. Results showed that the new sprayable membrane has good performance comparable with the conventional HDPE membrane and it can be a very attractive solution for tailings ponds liners.

Keywords: *tailings ponds, membrane, liners, laboratory tests, mechanical properties, chemical resistance*

1 Introduction

During mining excavation and processing, ore milling generates fine rock particles called tailings, which are left over from the process of separating the valuable fraction of an orebody from the gangue. Tailings can be pumped into ponds created from naturally existing valleys and secured by dams to allow the sedimentation of solids from the water. These impoundments serve the dual purpose of containing the tailings allowing the reuse of scarce water (US EPA 1994).

Because tailings may contain pollutants that contaminate soil and groundwater, adequate sealing materials are needed. Such liners retard the migration of leachate and its toxic constituents into underlying aquifers or nearby rivers, causing pollution of the local water. Several solutions are available to create a sealant barrier between the tailings and the ground, such as compacted earth, clays, chemicals and synthetic membranes (US EPA 1974). Modern structures present a layer of compacted clay with a minimum required thickness and a maximum allowable hydraulic conductivity lower than 1×10^{-9} m/sec (Benson et al. 1994; European Union Council Directive 1999) overlaid by a high-density polyethylene (HDPE) geomembrane.

Geosynthetic clay liners (GCLs) are also employed. These are thin (5–10 mm thick) manufactured liners that consist primarily of sodium bentonite that is either encased or sandwiched between two geotextiles or attached to a single polymer membrane (i.e. geomembrane) and held together by needle-punching, stitching, and/or gluing with an adhesive (Shackelford et al. 2010; Koerner 2012). In fact, sodium bentonite tends to swell as water is absorbed (Spagnoli et al. 2010) and can attenuate inorganic contaminants (Rubinos et al. 2015).

Synthetic liners are used to prevent seepage. They are classified as latexes and plastics, typically comprising polyvinyl chloride, neoprene and HDPE. Liner systems, in general, have a typical thickness of 1–600 mm and clay and plastic liner systems are often 600 mm thick, whereas a plastic plus GCL may be about 5 mm thick, with a life expectancy of 20 years (US EPA 1974). However, HDPE geomembrane for basal and side slope liners has a minimum thickness of 1.5 mm (Environmental Protection Authority Victoria 2015).

The purpose of a tailings pond liner is to minimise leakage of tailings water. An effective liner in a landfill system should be able to control water in terms of movement and protection of the environment (Dickinson & Brachman 2008). Waste water moves through the pond and downward towards the liner.

The aim of this paper is to present the results of a novel method of installing liners based on technology developed for waterproofing buildings. The investigation focused on membranes that could give the same or similar mechanical properties and chemical resistance, as well as durability, compared to conventional HDPE liners currently used in the mining industry. The key difference is that these novel lining systems differ in application method. They are spray-applied, overcoming the inherent performance issues of HDPE liners such as leakages at the location of welds, UV resistance, maintenance and repair. Two membranes were developed and tested and were preliminary coded as membranes 1678 and 1790. Hydraulic conductivity, mechanical (tensile, static puncture, tear resistance) and chemical tests (using synthetic and real tailings waste water) were performed. Results were compared with two HDPE materials (used for basements and landfills). The results showed that the sprayable membrane was an attractive solution compared to the conventional technology.

2 Material and methods

To control the leakage of fluids, different types of geosynthetic barriers are used, including polymeric, clay and bituminous type barriers. DIN EN 13493 (DIN 2013a) specifies the relevant characteristics of these geosynthetic barriers when used in the construction of solid waste storage and solid waste disposal sites, and the appropriate test methods to determine these characteristics. Solid waste here refers to solid form waste, including liquid–solid mixtures having the capability to be handled or mixed with solid waste for storage purposes.

Membranes 1678 and 1790, and the two chosen types of HDPE are all polymeric products. To test the polymeric geosynthetic barrier (GBR-P) related requirement, test methods shown in DIN EN 13493 (DIN 2013a) were followed. Test items in DIN EN 13493 (DIN 2013a) specified as A (relevant to all conditions for use) and H (required for harmonisation) are mandatory. The two new candidate products and HDPE are homogenous products, and in addition to general tests for thickness and mass, the following properties were assessed:

- Hydraulic properties – water permeability (liquid tightness).
- Mechanical properties – tensile strength, elongation, static puncture.
- Durability and chemical resistance – weathering, oxidation, ozone stress cracking test, leaching (water soluble), chemical resistance.

2.1 Hydraulic conductivity tests

To test hydraulic conductivity of impermeable layers, indirect methods such as oedometer tests (Colombo & Colleselli 1996) are recommended. Therefore, the Rowe cell was used, which was first described in Rowe and Barden (1966), while Head (1985) gives a detailed description of the principle and practice of Rowe cell testing. In the Rowe cell, the test sample is loaded hydraulically by water pressure acting on a flexible diaphragm (Figure 1). Drainage of the sample can be controlled and pore water pressure measured. Back pressure can be applied to simulate the in situ condition, whereas the conventional oedometer cannot provide back pressure. The application of hydraulic pressure and measurement of the variation of pore water pressure and volume change of the sample can be handled by either a conventional pressure panel or by an automatic system (Premchitt et al. 1995).

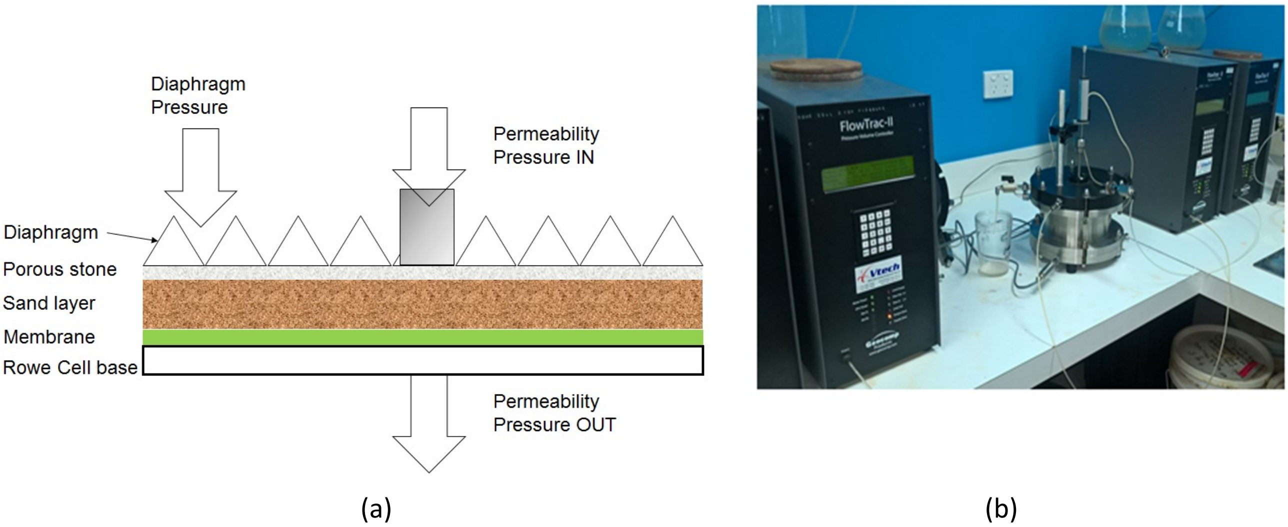

Figure 1 (a) Laboratory setup of the Rowe cell; (b) The cell used in the experiments

The Rowe cell possesses the control facilities for drainage and for the measurement of pore water pressure. It is capable of testing larger diameter soil samples compared to the oedometer cell (151.4 mm diameter versus 80 mm for the oedometer tests). Therefore, more reliable data can be obtained by using Rowe's cell because of the relatively smaller effect of structural viscosity in larger specimens.

One sample of membrane 1678 (2 mm thickness) and three samples of membrane 1790 (1.5, 2 and 4 mm thickness) were tested. The membrane was placed in the base of the Rowe cell and silicone was used to seal the outside edge of the membrane. The silicone was allowed to cure for three days before proceeding with the next step. This was the addition of a layer of sandy material (40% silica silt and 60% super fine sand by dry mass made up to 70% w/w solids) with tap water placed on top of the membrane. A porous stone was placed on top of the sandy material followed by the diaphragm, and the Rowe cell vessel was sealed. Pressure was hydraulically applied to the diaphragm and slowly brought up to 150 kPa of total stress, allowing the sample to consolidate. Once the vessel reached 150 kPa, the sample was left for 30 minutes to ensure the sandy material was fully consolidated. Permeability testing was applied using the constant head method, where 5 kPa of head pressure was applied to the sandy material and the membrane (while maintaining the 150 kPa of total stress to the sample). The permeability stage of the test was left for 48 hours. Once the permeability test was complete, the top of the Rowe cell was taken off and the height of the sandy material was measured.

Raw data was taken from the Rowe cell and used to calculate permeability, as per the following calculation:

$$K = \frac{QL}{Aht} \tag{1}$$

where:

K = hydraulic conductivity (permeability) (m/s).

Q = total water permeated through the sample (ml).

L = height of the sandy material/membrane (m).

A = cross-sectional area of the Rowe cell (m^2).

h = head pressure (kPa).

t = duration of test (s).

2.2 Mechanical tests

The polymeric geosynthetic membrane is a homogenous product designed to be applied on the bottom of tailings ponds. Tensile strength, elongation, static puncture and tear strength tests were undertaken to assess their mechanical performance (Figure 2).

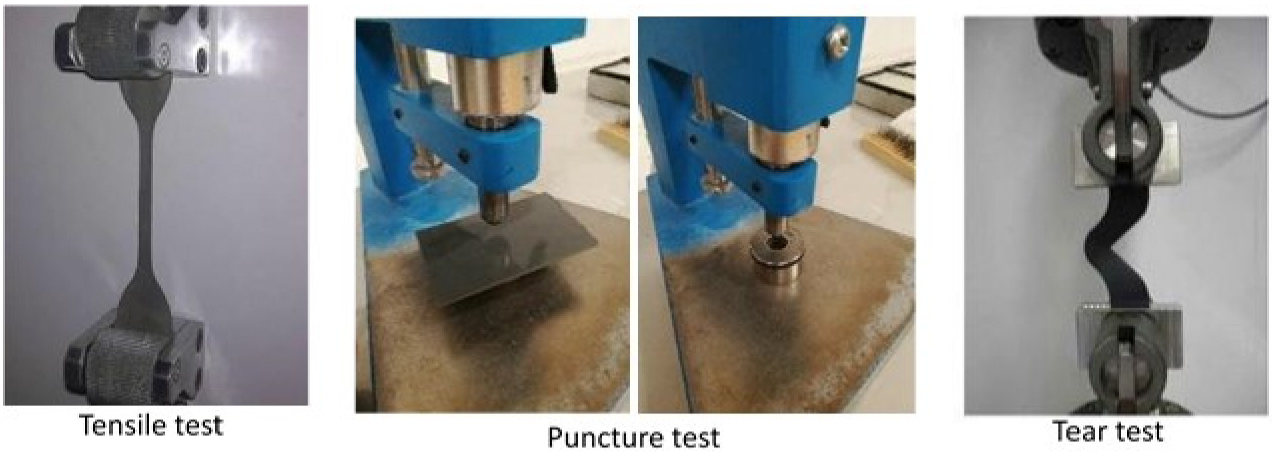

Figure 2 Picture of the mechanical tests performed on the membranes and HDPE products

For high elongation membrane, ISO 527-3 Type 5 specimen is recommended for tensile strength and the elongation test at a speed of 100 mm/min. Considering mechanical loading from solid waste, sharp edges of angular particles may exert a force on the polymeric membrane. Therefore, static puncture tests according to ISO 12236 (ISO 2006) were performed. As the polymeric barrier is going to be applied on the slope or inclined surface, tear strength according to BS ISO 34-1 Method B (BS 2015) was used.

2.3 Chemical and durability tests

Durability of GBR-P depends on various mechanisms that cause degradation. UV exposure, oxidative attack at elevated temperature, chemical attack, repetitive mechanical stress and leachate characteristics directly or indirectly affect its mechanical properties or its resistance to other forms of degradation. All of these aspects will cause degradation and affect durability.

Membranes 1678 and 1790 are thermoset elastomers, while HDPE is classified as a polyolefin GBR, and GBR. Therefore, different test methods are applied for assessing environmental stress cracking. Other test methods are applicable for both membranes 1678, 1790, and HDPE, regarding weathering, resistance to oxidation, resistance to leaching and chemical resistance.

2.3.1 Weathering

An accelerated method was used, involving a controlled environment in which specimens were exposed to alternative periods of UV light and water spray. The specimens were tested with radiant exposure of 350 MJ/m^2 at 50°C for five hours, then sprayed with water at 25°C for one hour, with a testing time of 3,000 hours. This is suitable to GBR that will be exposed for one year.

2.3.2 Resistance to oxidation

BS EN 14575 (BS 2005) modified Method C1 was recommended – exposing the membrane at 85°C for 90 days.

2.3.3 *Resistance to leaching*

As described in DIN EN 13493 (DIN 2013a), the GBR-P shall be tested for its resistance to leaching by specified liquid in accordance with BS EN 14415 (BS 2004b):

- Method B: Immersing the membrane in saturated $Ca(OH)_2$ for 56 days at 20°C.
- Method C: Immersing the membrane in a mixture of 30% methanol/30% isopropanol/40% glycol for 56 days at 20°C.

2.3.4 *Chemical resistance*

GBR-P employed in solid waste storage facilities shall be tested in accordance with BS EN 14414 (BS 2004a), procedure A (acid), B (alkali), C (organic solvent) and D (synthetic leachate).

Site-specific conditions may affect the durability of GBR-P and design life. This can be tested by using site-specific leachate, according to BS EN 14414 (BS 2004a), procedure E.

- Procedure A: Immersing the membrane in 10% H_2SO_4 at 50°C for 56 days.
- Procedure B: Immersing the membrane in saturated $Ca(OH)_2$ for 56 days at 50°C.
- Procedure C: Immersing the membrane in 35% diesel fuel/35% paraffin C_{10}–C_{20}/30% lubricating oil HD30 for 56 days at 50°C.
- Procedure D: Immersing the membrane in synthetic leachate for 56 days at 50°C.
- Procedure E: Immersing the membrane in site-specific leachate.

2.3.5 *Environment stress cracking test*

Since membranes 1678, 1790, and HDPE have a non-crystalline structure, an ozone stress cracking test was performed according to DIN EN 1844 (DIN 2013b). Refer to Figure 3 for the test equipment used. The specimens were maintained at 20% deformation for 336 hours in an atmosphere of 40°C, humidity 65% and ozone concentration of (200±20) ppm by volume.

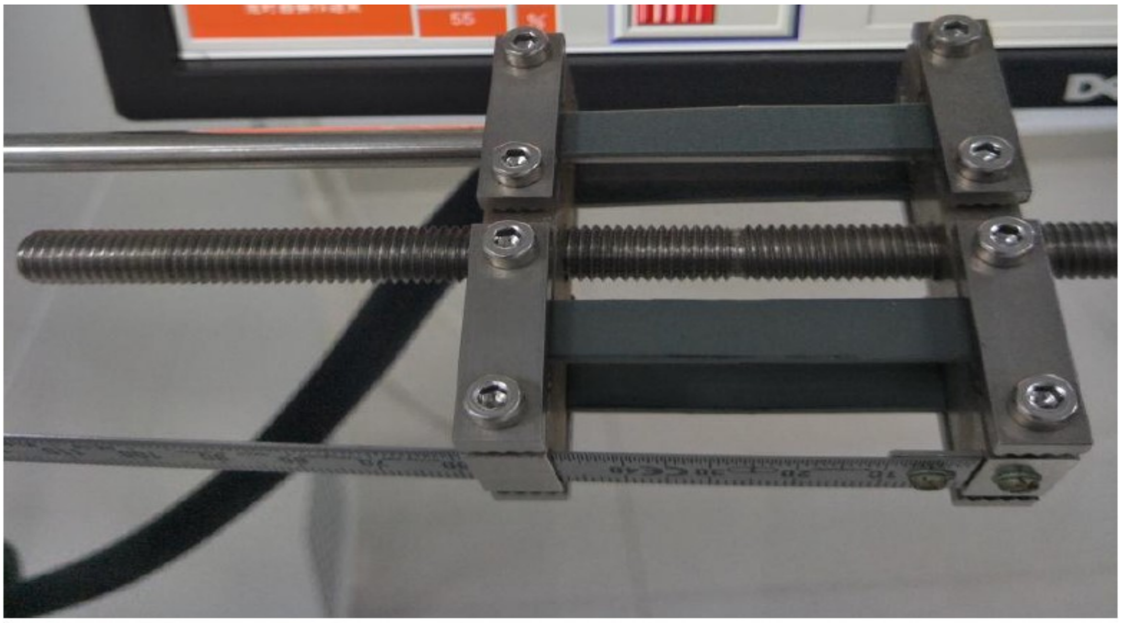

Figure 3 Stress cracking test

3 Results and discussion

3.1 Hydraulic conductivity tests

The permeability test results are shown in Table 1. Testing was initially conducted on the artificial soil with a porous stone in place of a membrane inside the Rowe cell to get baseline permeability data. The sample was under permeability testing for 24 hours where 6.28 ml of water was displaced through the sample, which equated to a permeability of 2.60×10^{-5} m/s, as was expected due to the nature of the artificial soil.

Table 1 Hydraulic permeability tests performed on the artificial soils and the membranes

Material	Time (s)	K (m/s)
Soil	83,953	2.60×10^{-5}
1678 (2 mm membrane)	173,040	≈ 0
1790 (1.5 mm membrane)	173,040	≈ 0
1790 (2 mm membrane)	173,040	≈ 0
1790 (4 mm membrane)	173,040	≈ 0

The permeability test was carried out on supplied samples 1698 (2 mm thick) and 1790 (1.5, 2 and 4 mm thick). There was a negative water displacement for all the samples tested because the membrane proved to be impermeable and the artificial soil slowly consolidated under 5 kPa of pressure as water within the soil was pushed back into the pump. Because tap water was used, further tests were performed to assess the chemical resistance of the membranes.

3.2 Mechanical properties

Mechanical properties of the different membranes tested are shown in Table 2.

Table 2 Mechanical properties tests performed with different membranes

Properties	Tensile strength (MPa)	Elongation (%)	Static puncture (J)	Tear strength (N)
1790	21.5	7.5	0.2	175
1678	21.2	470.0	7	120
HDPE (landfill)	21.4	500.0	4	195
HDPE (basement)*	15.7	480.0	4*	145

*All of the samples were 2 mm thick, except for HDPE membrane (basement) where 1 mm thickness sample was used.

Membrane 1678 and the two types of HDPE gave similar mechanical properties. Membrane 1678 was slightly superior with respect to the HDPEs regarding resistance by static puncture test but it has a slightly lower tear strength.

Although DIN EN 13493 (DIN EN 2013a) did not give specification for mechanical properties, from the ozone environment stress cracking test method description, it is known that the sample will be maintained at 20% deformation for 336 hours without cracking. With 7.5% elongation, it seems that membrane 1790 is too brittle to be used for waste solid storage.

3.3 Chemical and durability tests

All durability tests are carried out by first exposing a specimen to simulated and/or accelerated environments under controlled conditions, followed by tensile strength and elongation tests with the exposed specimen. An unexposed control sample must undergo the same test and the comparison ratio of the exposed specimen to the controlled sample provides the basis for acceptance. According to DIN EN 13493 (DIN 2013a), the acceptance criteria shall be retained for values of at least 75% of the original tensile strength, and at least 75% of the original elongation at failure. Both criteria need to be satisfied. The only exception to this rule is the test for ozone environment stress cracking, which can be assessed by single sample testing.

3.3.1 Weathering

Weathering resistance results after exposure to UV radiation for 3,000 hours are shown in Table 3. Except for the HDPE used for basements, all other GBR-P materials after 3,000 hours testing yielded strength and elongation retention rates of more than 75%.

Table 3 UV resistance 3,000 hours test

UV resistance (3,000 hrs)	Tensile strength retention rate (%)	Elongation retention rate (%)
1790	93.5	77.3
1678	87.3	91.5
HDPE (landfill)	97.7	96.0
HDPE (basement)	71.3	114.6

3.3.2 Resistance to oxidation

As GBR-Ps are used for solid waste disposal, it is recommended to expose the membrane to thermal degradation testing at 85°C for 90 days. Tests were performed at 80°C for 90 days and the results are provided in Table 4.

Table 4 Thermal degradation test result

Resistance to oxidation 90 days @ 80°C air	Tensile strength retention (%)	Elongation retention (%)
1790	113.0	68.0
1678	101.9	104.3
HDPE (landfill)	100.9	108.0
HDPE (basement)	41.4	12.1

The results in Table 4 reflect that membrane 1678 and HDPE (landfill) are stable when exposed to thermal conditions. The poor performance of HDPE (basement) is not related to the sample thickness; rather it is related to additives present in the HDPE. With a thermal stable anti-oxidant additive, the retention will be higher.

3.3.3 Resistance to leaching

The test was performed with two different leaching environments, with the results shown in Table 5. From the above results, it is possible to see that all products passed in condition B when immersed in saturated $Ca(OH)_2$. When immersed in condition C, the mixture of small molecular weight organic alcohol, all materials showed unsatisfactory behaviour, except HDPE (landfill). That means that the other products can only be used in constrained conditions. For example, membrane 1678 is not recommended to be used where the presence of small organic compounds is likely. However, for tailings ponds with an inorganic environment, all of the novel membranes performed well.

Table 5 GBR-P resistance to leaching

Resistance to leaching	Test condition	1790		1678		HDPE (landfill)		HDPE (basement)	
		Ten r r*	E r r**	Ten r r	E r r	Ten r r	E r r	Ten r r	E r r
B: Saturated $Ca(OH)_2$	56 days @ 20°C	99%	127%	105%	104%	95%	106%	81%	88%
C: 30.V% methanol/30.V% isopropanol/40.V% glycol	56 days @ 20°C	20%	533%	38%	70%	97%	104%	72%	83%

*Ten r r: Abbreviation for tensile strength retention rate.
**E r r: Abbreviation for elongation retention rate.

3.3.4 Chemical resistance

Chemical resistance tests were not only performed for the synthetic leachates (Table 5) but also for the in situ leachates collected from mines in China and Australia.

As was the case for resistance to synthetic leachates in Table 5, only HDPE (landfill) passed all the conditions studied. Membrane 1678 performs unsatisfactorily under synthetic leachate conditions. The synthetic leachate contains an amount of organic acid like acetic acid, propionic acid, etc. Tables 5 and 6 show that 1678 is not resistant to organic alcohol or organic acid (small molecule organic compounds) but is resistant to diluted inorganic acid, alkali and certain types of solvents.

Table 6 Resistance to chemicals

Resistance to chemicals	Test condition	1790		1678		HDPE (landfill)		HDPE (basement)	
		Ten r r*	E r r**	Ten r r	E r r	Ten r r	E r r	Ten r r	E r r
A: 10% H_2SO_4	56 days @ 50°C	105%	87%	86%	85%	96%	108%	62%	65%
B: Saturated $Ca(OH)_2$	56 days @ 50°C	97%	129%	100%	100%	94%	113%	77%	84%
C: 35.V% diesel fuel/35.V% paraffin C10–C20/ 30.V% lubricating oil	56 days @ 50°C	104%	88%	83%	99%	96%	110%	69%	85%
D: Synthetic leachate	56 days @ 50°C	64%	116%	28%	51%	95%	112%	66%	73%
E1: Site leachate from China	56 days @ 50°C	105%	123%	81%	102%	94%	109%	80%	83%
E2: Site leachate from Australia	56 days @ 50°C	108%	133%	78%	104%	95%	117%	78%	88%

*Ten r r: abbreviation for tensile strength retention rate.
**E r r: abbreviation for elongation retention rate.

Real site leachates from China and Australia were also used to assess the properties of the products tested (Table 7).

It is noteworthy that leachates from some mine sites are less aggressive than the synthetic leachates tested. Based on the results, it is possible to state that membrane 1678 is a good candidate to be used in solid waste storage application where inorganic conditions exist.

Table 7 Site leachate composition analysis result

XRF	Site leachate from China (mg/l)	Site leachate from Australia (mg/l)
Na	4,351.2	4,701.0
S	534.12	1,657.3
Mg	n/a	1,363.0
P	380.4	331.80
Ca	371.2	719.9
Cl	272.8	1,319.9
Gd (Gadolinium)	86.7	62.1
K	84.2	241.9
Cu	34.7	25.9
Co	30. 6	n/a
Fe	29.17	n/a
Mn	24.2	n/a
Dy (Dysprosium)	n/a	89.6
Ho (Holmium)	n/a	41.5
$C_6H_{10}O_5$	12.5 mg/cm^2	12.5 mg/cm^2
Site leachate composition analysis result		
$CaSO_4$	0.05~0.10 (%)	0.05~0.10 (%)
Na_2SO_3	0.05~0.10 (%)	0.05~0.10 (%)
$MgSO_4$	–	0.05~0.10 (%)
H_2O	<100 (%)	<100 (%)
pH Value	6	6

3.3.5 Environment stress cracking test

Membrane 1678 did not show any cracking and passed the environment stress cracking test. However, membrane 1790 does not seem to be a suitable product since the elongation retention ratio is low (<20%).

4 Spray-applied liner installation

The alternative lining system is based on spray application, using reactive resin technology. It is proposed that it can be used for brine, tailings and overflow ponds on mine sites that require low permeability and high durability to minimise leakage of contaminated water into the environment. It overcomes the difficulties related to the use of HDPE liners, such as leakages at the location of welds, resistance to UV, and maintenance and repair. A spray-applied product will result in a continuous membrane without the need of welding and it is easy to apply, with high application rates.

The membrane is applied by hot spraying onto a suitable polypropylene geotextile to the required thickness (Figure 4). The membrane will adhere to the geotextile resulting in a rigid, durable but flexible membrane.

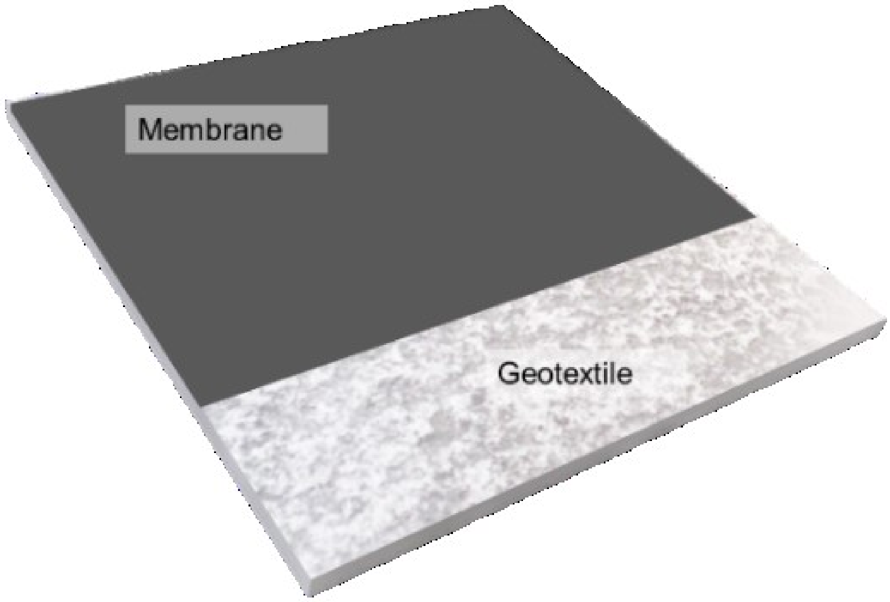

Figure 4 Sketch of spray-applied system setup

Before laying down the geotextile, the substrate must be levelled and be as smooth as possible and free from irregularities or sharp edges that can puncture the membrane, similar to the surface preparation required for an HDPE liner. The geotextile should have a specific weight of 150–200 g/m², depending on the substrate and should be based on a non-woven virgin polypropylene. It is loose laid and must be free from tension, folds and wrinkles, with approximately 15–20 cm overlap at the edges. It must be placed in direct contact with the ground, avoiding any gaps or voids between the substrate and the geotextile. For fixation, the edges can be spot welded using a hot air gun. The distance between the spot weldings will depend on the layout and size of the pond. The welding must ensure that the geotextile will not slip during application of the membrane.

The membrane is a two-component system and the A and B components are applied 1:1 by volume, plural component and a high-pressure metering machine (Figure 5). The machine must be capable of maintaining component temperatures of at least 65°C at the spray gun, as well as operating pressures of between 200 and 240 bars. For the pressurised mix, an airless spray gun with changeable spray tips for the optimisation of the spray pattern will be required. Due to the elevated application temperature, the gel time of the product is approximately 10 seconds and is tack free after 1–2 minutes. This allows fast application and use of the lining system. The application can be continuous, but in case of unexpected interruptions exceeding a site-specified time, a primer has to be applied on the already cured membrane.

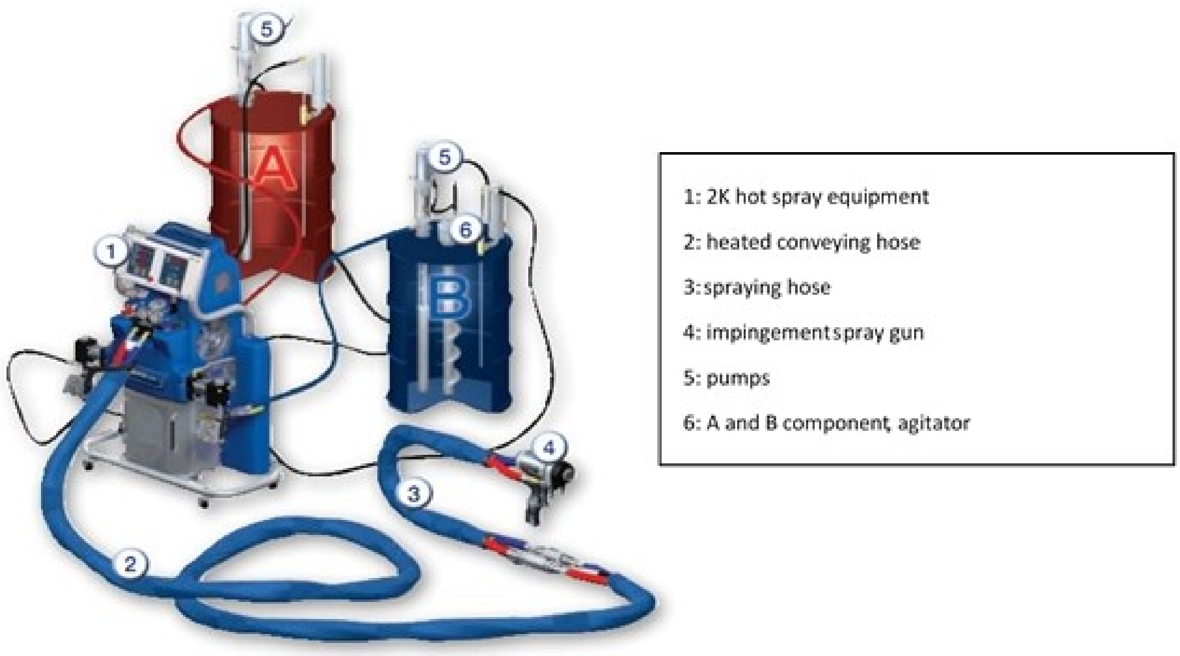

Figure 5 Machine used for the spray tests: 2K hot spray machine

5 Conclusion

The purpose of a tailings pond liner is to minimise leakage of the tailings water. Typically, HDPE liners are currently used in the mining industry. BASF has investigated the suitability of alternative reactive membranes to provide the same protection and chemical resistance as the conventional HDPE lining system. Two membranes were selected and tested and were preliminary coded as 1678 and 1790. Permeability tests with the Rowe cell, chemical and durability tests (interaction with water and leachates at different temperatures, oxidation and UV resistance tests), and mechanical tests (tensile strength tests, elongation tests, puncture tests) were performed on the novel membranes and benchmarked against the HDPE sheet membranes.

Based on the test results, it can be concluded that the sprayable membrane 1678 is an alternative for the HDPE sheet membranes as used in the mining industry. Mechanical performance and chemical resistance are similar and it is expected that durability after application could be better than the HDPE. Moreover, membrane 1678 may be superior to HDPE liners in respect to leaks at the welding location, resistance to UV, as well as maintenance and repair. It could also result in a seamless membrane, which is easy to apply and has high application rates. The technology and chemistry used in the formulation of these membranes have been employed for years in the flooring industry and protection of roofs. Their use in tailings containment is a logical extension of this application.

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