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PROOFS

Ten-year PVC geomembrane durability

E. J. Newman[1] and T. D. Stark[2]

[1] *Graduate Research Assistant, 2217 Newmark Civil Engineering Laboratory, University of Illinois, 205 N. Mathews Ave., Urbana, IL 61801, USA, Telephone: +1 217 333 6941, Telefax: +1 217 333 9464, E-mail: ejnewman@uiuc.edu*

[2] *Professor of Civil Engineering, 2217 Newmark Civil Engineering Laboratory, University of Illinois, 205 N. Mathews Ave., Urbana, IL 61801, USA, Telephone: +1 217 333 7394, Telefax: +1 217 333 9464, E-mail: tstark@uiuc.edu.*

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ABSTRACT: The 10-year results of an ongoing study on the long-term performance of a PVC geomembrane in northern Minnesota are presented. Samples of PVC geomembrane and seams are exhumed periodically over a 30-year period and tested to measure the certified, index, and seam properties of the exhumed geomembrane and seams. Results are compared with the material specification existing at the time of installation as well as with the current PVC geomembrane specification prepared by the PVC Geomembrane Institute. All material properties except for thickness meet both specifications. Material properties measured at the laboratory and field moisture conditions are compared, and indicate that testing at the field moisture condition is more representative of the field performance than after laboratory desiccation. Data measured over a ten-year period suggest that the in situ moisture condition may counteract some, if not all, of the plasticizer migration that occurs in this application, and plasticizer migration slows as the geomembrane becomes acclimated to the field environment.

KEYWORDS: Geosynthetics, Geomembranes, Durability, Mining, Containment, PVC geomembrane

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1. INTRODUCTION

PVC geomembranes have been used successfully in numerous lining applications, such as landfills, waste lagoons, reservoirs, dams, and canals (Koerner *et al.* 2008). In general, PVC geomembranes exhibit good interface strengths (Hillman and Stark 2001), which facilitates these applications, but over-steepened slopes can still pose problems (Stark *et al.* 2008). Another concern with PVC geomembranes in these applications is long-term durability. This paper describes a project that is being conducted to investigate the long-term durability of PVC geomembranes.

In spring of 1994, the Minnesota Department of Natural Resources (MDNR) issued a request for proposals (RFP) to line a mine settling basin at one of its sites in Hibbing, Minnesota. Hibbing is located about 300 km north-east of Minneapolis. A PVC geomembrane contractor responded to the RFP and was awarded a contract to line the basin. The PVC Geomembrane Institute (PGI) contacted the MDNR and proposed a cooperative research project on behalf of its members to study the long-term durability of 0.76 mm PVC geomembranes in a cold (average temperature of 3°C) climate using the geomembrane that was to be installed in the basin by the contractor. In 1995 the settling basin was lined with a 0.76 mm-thick PVC geomembrane, and three test coupons were placed on top of the installed liner system, as shown in Figure 1. These coupons are not part of the actual liner system, and can be removed without damaging the installed liner system. 1

PVC material from three manufacturers was used, along with different two seam types (chemical fusion weld and hot wedge weld), for the three test coupons. Geomembrane samples A, B, and C were manufactured by Oxychem (Oxy), Nanya (Nan), and Canadian General Tower (CGT), respectively, as shown in Figure 1. The locations of the coupons are marked with orange plastic cones, which are submerged when the basin is filled, so the samples can be located at later times. After placement of the coupons, they were covered with 75 mm of protective sand cover. Along with the cones and the sample coupons, steel plates with the manufacturer's name and the seam type were buried with each coupon (see Figure 2). These coupons are to be excavated at specified dates, and samples cut from the coupons for testing to evaluate geomembrane durability with time. The adopted sampling frequency is 2, 4, 5, 10, 15, 20, 25, and 30 years. This paper reports the results of the 2-, 4-, 5-, and 10-year

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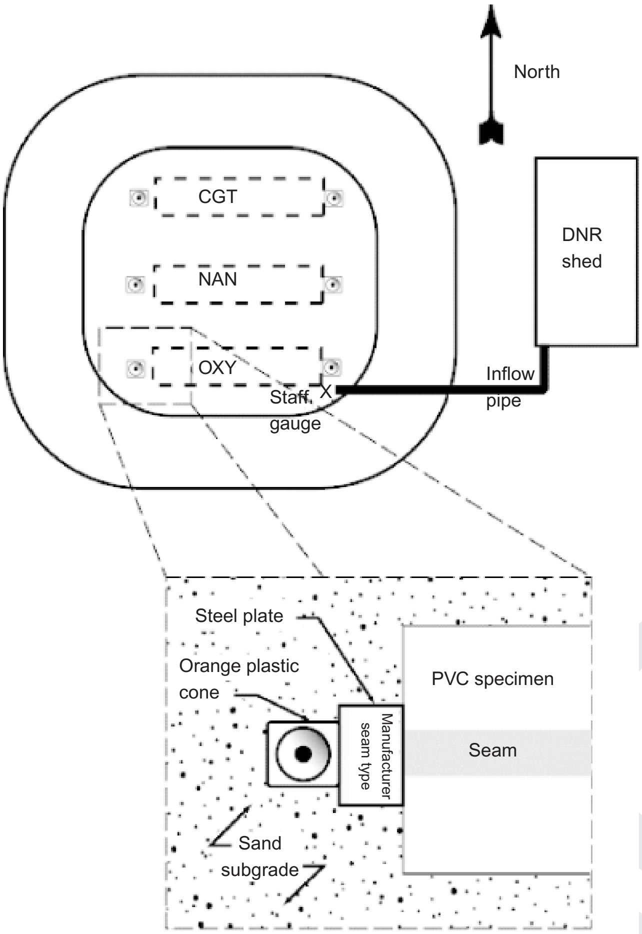


Figure 1. Map showing settling basin and location of PVC test coupons relative to orange marker cones

Figure 2. Orange cone and steel plate marking the location of a test coupon during excavation of 10-year samples

samples, with the 10-year sample being excavated and tested in 2005.

On 3 August 2005 the first author drove to the Hibbing site to collect the 10-year samples for testing. A procedure was followed to ensure that the samples stayed moist until they could be stored in a controlled environment at the University of Illinois in Urbana-Champaign (UI). This was undertaken so that the samples could be tested at field moisture conditions to reflect the field behavior of the material, instead of allowing it to desiccate.

At the site, the ends of the sample coupons were uncovered one at a time and 0.7 m of geomembrane cut from each coupon. Some sand was left stuck to the geomembrane samples to maintain a moist environment during transportation. After cutting the coupons, the samples were rolled up and placed inside thick, double-layered plastic bags to prevent desiccation. The cones and marking plates were replaced at the edge of the remaining coupon to facilitate future sample collection in five years, that is, year 15.

Each sample obtained was 0.7 m long in the machine direction (MD) and 1.8 m long in the transverse direction (TD). The machine direction is the direction in which the sheet of PVC was extruded during the manufacturing process, and in which the long PVC molecules tend to be oriented. The excavated seam runs parallel to the machine direction, and is included in the total width of the sample. After returning to the UI, the sand was cleaned off the geomembranes and the samples were cut into the following three pieces: one 0.3 m × 2.8 m piece containing the seam, and two 0.7 m × 0.8 m pieces, one for use in desiccated tests in accordance with ASTM test methods, and one for testing in the in situ moisture condition. The desiccated samples were allowed to acclimatize to the laboratory temperature and humidity, which dried them out. The in situ samples were kept in a moisture room to simulate the moisture condition that they would be at in the settling basin/field. After each sample had been cleaned and cut into the three samples listed above, appropriately sized test specimens were cut for each test.

2. TESTING

Two series of tests were performed: one series utilized the *Standard Practice for Conditioning Plastics for Testing* (ASTM D618) Method A procedure, which includes desiccating the material in the laboratory prior to testing; the other procedure varied from ASTM D618 Method A by maintaining the field moisture condition prior to and during testing. Maintaining the field moisture condition allows the field performance of the material to be evaluated and compared with the ASTM preparation procedure. To evaluate the field performance of an excavated geomembrane, it is recommended by the PGI and PVC geomembrane manufacturers and contractors that the geomembrane be tested under field conditions, not in an artificially created condition that does not represent the field (i.e. desiccated).

The test results from both series are compared both with the National Sanitation Foundation Specification (NSF-54 1993), and with the PGI Specification 1104 (PGI 2004). The NSF-54 specification was the applicable standard in 1995 when the material was manufactured and installed at the site. To further evaluate the performance of the geomembrane, the corresponding values of the PGI-1104 specification are also presented for each test. The PGI-1104 specification, which became effective on 1 January 2004, was developed by the PGI to fill the void left by the obsolescence of NSF-54, which was last updated in 1993.

The three main categories of material properties measured in both series are the certification properties, index properties, and seam properties. The certification properties are typically measured during the manufacturing process at a frequency of once per lot or per 18 000 kg of material, whichever comes first (PGI 2004). The certification properties are documented for each lot of material produced. The index properties are measured and documented only once for a particular geomembrane formulation (PGI 2004). The seam properties are typically measured as dictated by the installer's quality control procedures for a particular application. Frequently, the seam properties are measured every 170 linear meters of seam.

The results presented below are for testing of the 10-year samples, as well for the 2-, 4-, and 5-year samples. The testing of the 2-, 4-, and 5-year samples also was performed at the UI within two to three months after recovery of the samples in each of those years.

2.1. Specified geomembrane properties

2.1.1. *Material thickness*

The first property measured as part of the testing program was the thickness of the PVC geomembrane. According to the NSF-54 specification, the thickness should be measured using the *Standard Specification for Nonrigid Vinyl Chloride Plastic Film and Sheeting* (ASTM D1593). This requires the specific gravity and mass and area of a specimen to be measured, and the nominal thickness to be calculated using these measurements, instead of measuring thickness directly. The PGI-1104 specification uses the *Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings* (ASTM D1599) to measure thickness. ASTM D1599 involves direct measurement of the thickness using a micrometer built specifically for measuring geomembrane thickness. The 0-year and 2-year samples were measured using ASTM D1593, and the 4-year, 5-year, and 10-year samples were measured using ASTM D1599. It is anticipated that the different test procedures contributed to some of the variations in thickness observed during the testing, because the thickness of a PVC geomembrane generally does not change significantly. Material properties measured at installation are available only for Samples A and B.

Both the NSF-54 and PGI-1104 specifications require a nominal thickness of 0.76 mm ± 5%. This corresponds to a minimum allowable thickness of 0.72 mm and a maximum allowable thickness of 0.80 mm. Figure 3 shows that the thickness of all of the samples increased between 2 and 4 years, probably because of the use of ASTM D1593 and the calculation of thickness. The thickness increased or stayed the same for the 4- and 5-year samples. However, some of the samples decreased in thickness from 5 to 10 years (e.g. Specimen B).

This decrease in thickness between the 5-year and 10-year samples may be attributed to material variability across the sheet, because the samples obtained each year correspond to a different location on the geomembrane, as well as to testing variability. The variability also may be caused by the 2- and 4-year thicknesses being measured using ASTM D1593 whereas the 5- and 10-year thicknesses were measured using ASTM D1599. The only visible trend in the thickness measurements is a small decrease in thickness for all the specimens between the 5- and 10-year measurements.

2.1.2. *Tensile properties*

The tensile break strength of a PVC geomembrane is the maximum tensile force required to break a 150 mm × 25 mm standard tensile specimen. The specimens are tested according to the *Standard Test Method for Tensile Properties of Thin Plastic Sheeting* (ASTM D882) Method A at a rate of elongation of 500 mm/min. Figure 4 presents the break strength of the various exhumed materials. It shows that all the specimens meet the required minimum break strength of 12.1 kN/m under the NSF-54 specification and 12.8 kN/m under the PGI-1104 specification. Thus 10 years of field exposure has not significantly affected the tensile strength of the buried PVC geomembranes. In addition, there is no significant increase in tensile resistance with time, which would have indicated a continuing loss of plasticizer over the 10 years for whicht the geomembranes were exposed to in situ conditions, because the material would become stiffer with plasticizer loss.

Figure 5a shows that break strengths in the machine direction (MD) tend to be higher than in the transverse direction (TD). This is to be expected, because the machine direction is the direction in which the long PVC molecules tend to be oriented. Figure 5b shows that there

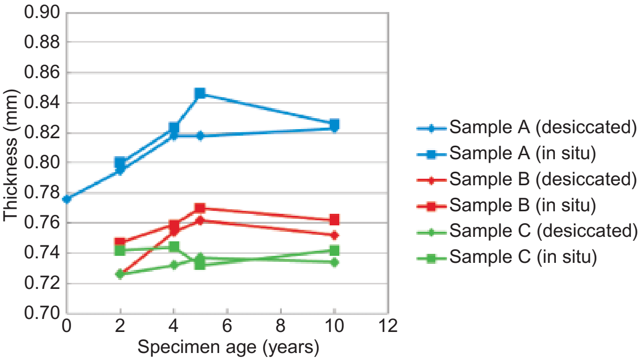


Figure 3. Specimen thickness as a function of specimen age

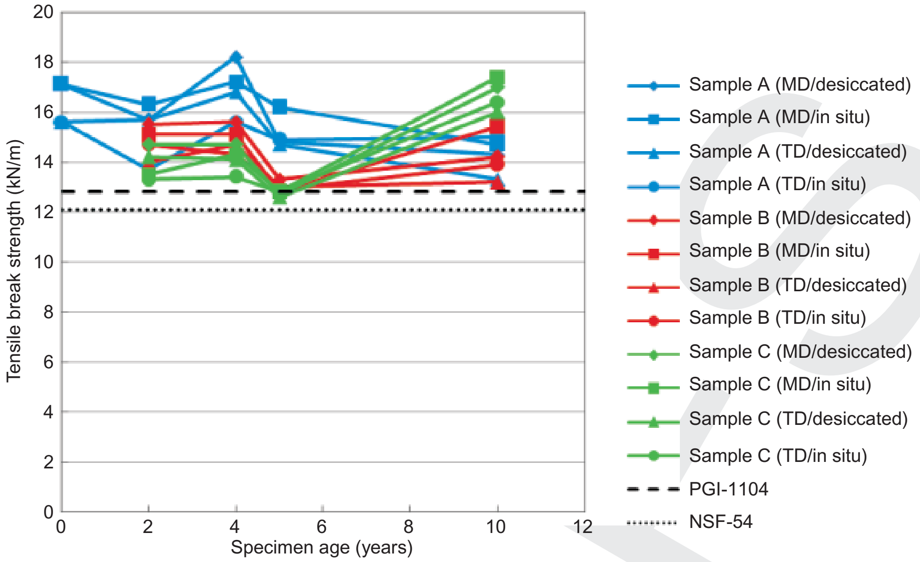
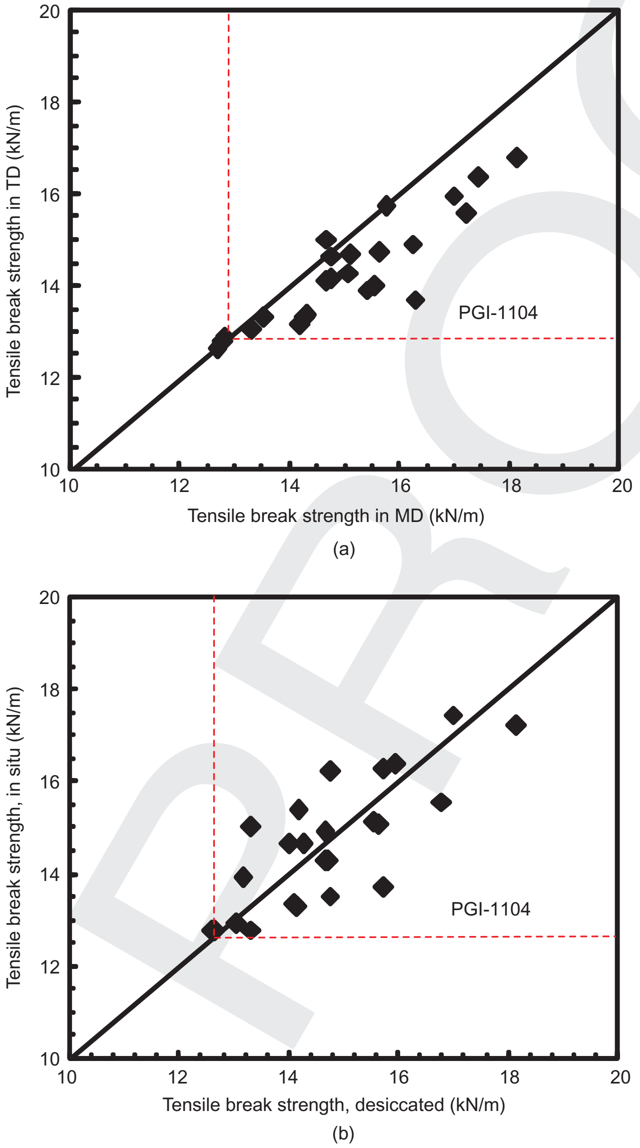


Figure 4. Tensile break strength as a function of specimen age



(a)

(b)

Figure 5. Effect of (a) orientation and (b) moisture condition on tensile break strength

is no trend with respect to the desiccated and in situ condition or the age of the specimens. The PGI-1104 required minimum break strength of 12.8 kN/m, which exceeds the NSF-54 value of 12.1 kN/m, is superimposed in Figures 6a and 6b to show that all the data exceed both of these specifications.

Another property measured using ASTM D882 (Method A) is the elongation at break. A decrease in elongation at break over time indicates that the material is becoming more brittle with time which usually reflects a loss of plasticizer. Plasticizer migration occurs initially as the geomembrane comes to equilibrium with the field conditions and stops within a few years after the geomembrane has adjusted to the new environment (Choi and Stark 2005). For the cases reported by Choi and Stark (2005), plasticizer loss usually occurred at the surface of the geomembrane, did not exceed 10–30% of the initial plasticizer content, and decreased with time, as suggested by Giroud (1995) and Giroud and Tisinger (1995). The NSF-54 specification requires a minimum elongation at break of 325% for a 0.76 mm-thick PVC geomembrane, whereas the PGI-1104 specification requires a minimum of 380%, that is, a more flexible material. Figure 6 presents the elongation at break, as a percentage, for each of the specimens tested as a function of specimen age. All of the specimens tested meet both the NSF-54 and the PGI-1104 specifications by a wide margin. For example, the smallest value of elongation at break measured is 389% for the 5-year, machine direction, and desiccated specimen. The flexibility, and thus large elongation at break, is illustrated in Figure 7, which shows the elongation during a typical tensile test on a PVC geomembrane. 2

Figure 8a shows that the tensile elongation at break tends to be slightly greater in the transverse direction than in the machine direction. This is in agreement with the secant moduli at 100% strain being larger in the transverse direction, as discussed below. There is no clear trend in the elongation at break with respect to specimen condition (i.e. desiccated or field moisture) or age as shown in

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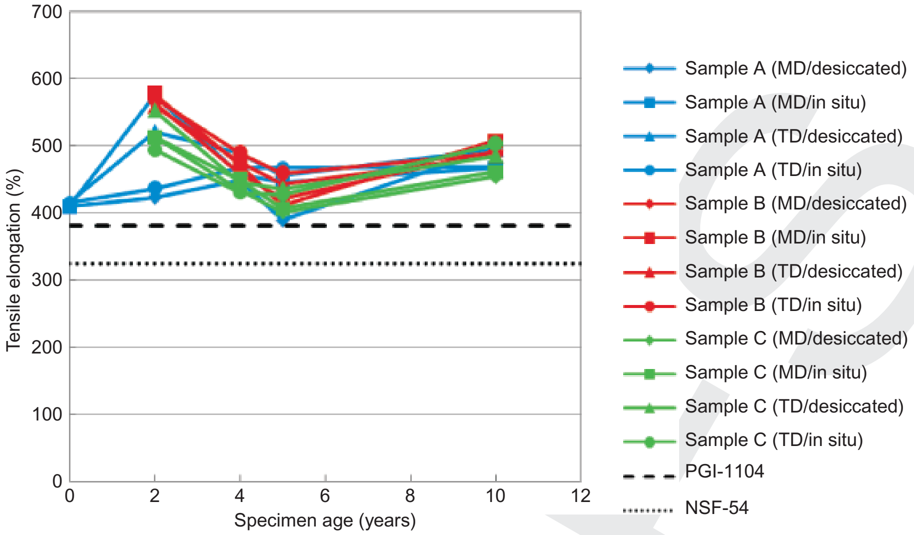

Figure 6. Tensile elongation at break in percent

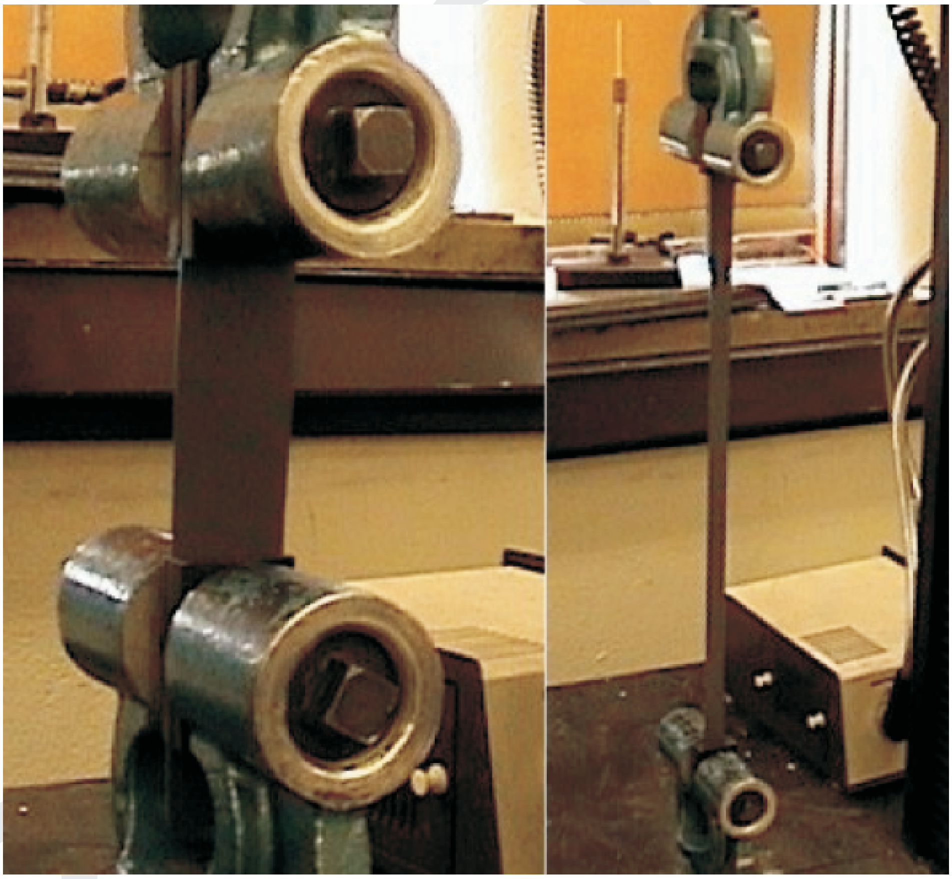

Figure 7. PVC geomembrane before and during tensile testing

Figure 8b and Figure 6. However, the data show more variability with the desiccated specimens, as well as an increase in flexibility with time, instead of decreasing with time as expected with plasticizer migration for some of the in situ moisture samples. For example, two of the three in situ moisture and transverse direction specimens show an increase in flexibility from 2 years to 10 years. Thus the moist environment may be compensating for the small amount of plasticizer migration that might be occurring. The plasticizer migration is small after 10 years because most of the in situ moisture condition specimens show a small reduction in elongation at break from 2 to 10 years.

The last quantity reported as part of the ASTM D882 (Method A) testing is the secant modulus at 100% strain. This corresponds to the load required to double the length of the tensile specimen. A large value of secant modulus at 100% strain corresponds to a stiff material, whereas a smaller value corresponds to a more flexible material,

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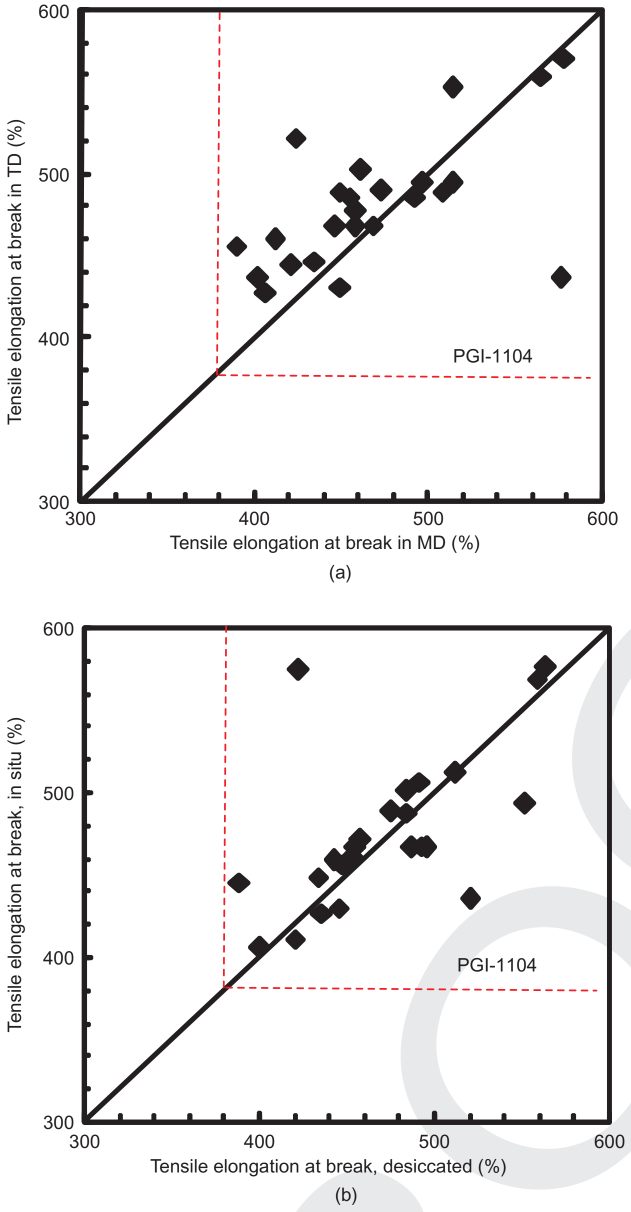

Figure 8. Effect of (a) orientation and (b) moisture condition on elongation at break

which means a higher plasticizer retention. The minimum required secant modulus at 100% strain for the NSF-54 specification is 5.3 kN/m, whereas the minimum for the PGI-1104 specification is 5.6 kN/m. All of the values presented in Figure 9 comfortably meet the required specification values.

As with the tensile break strengths, Figure 10a shows that the secant moduli at 100% strain tend to be higher in the machine direction than in the transverse direction. This indicates that the orientation of the PVC molecules in the machine direction results in a higher strength and stiffness in this direction, but not necessarily a larger maximum strain. Additionally, Figure 10b shows that the in situ moisture condition results in a lower secant modulus at 100% strain, and thus a more flexible material. The data show that the secant modulus decreased or stayed about the same for the in situ moisture condition specimens except for Manufacturer C, which increased. This suggests that the increase in stiffness with time may be dependent on the formulation of the PVC geomembrane. These data also indicate that the moist environment may be compensating for the small amount of plasticizer migration that might have occurred in the field.

2.1.3. *Tear resistance*

In addition to the traditional tensile tests performed to measure the properties above, a tear resistance test (ASTM D1004) is performed on notched specimens (see Figure 11) as another measure of the strength and toughness of the PVC geomembrane. The tear resistance test is performed at a rate of elongation of 51 mm/min. The minimum required tear resistance for both the NSF-54 and PGI-1104 specifications is 35 N. The results of this test are presented in Figure 12: they show that all the specimens exceed both specifications.

Figures 13a and 13b show that the MD and desiccated moisture condition specimens exhibit higher tear resistance than the TD and in situ moisture condition specimens, respectively. This is in agreement with the higher strength and stiffness observed for the MD and desiccated

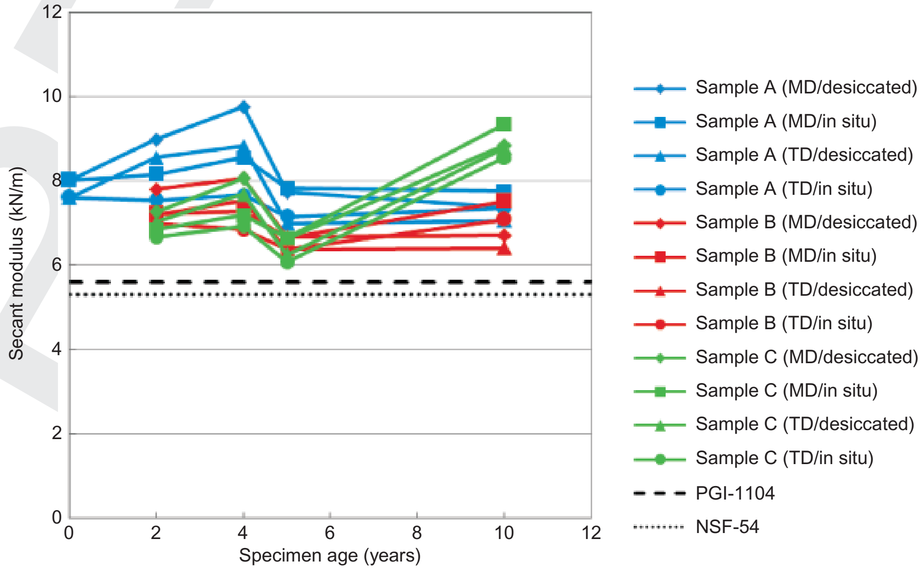

Figure 9. Secant modulus at 100% strain as a function of specimen age

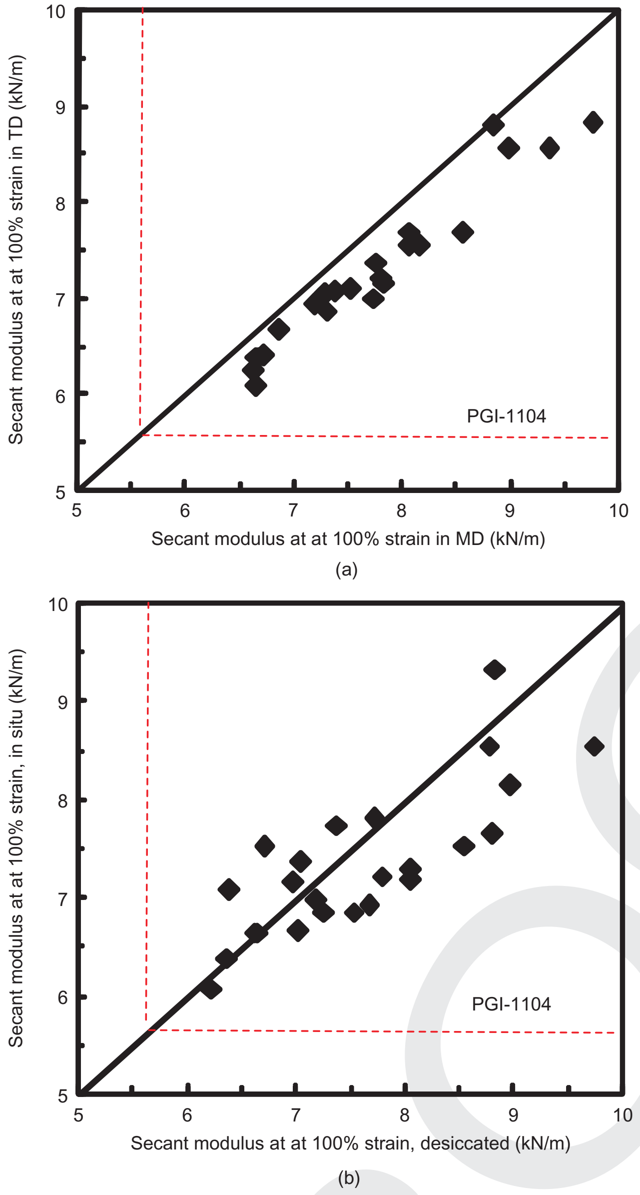

Figure 10. Effect of (a) orientation and (b) moisture condition on secant modulus at 100% strain

moisture condition specimens in the tensile testing. There is no clear trend in the tear resistance with respect to specimen age, although one half of the in situ moisture-conditioned specimens show a decrease or no change in the tear resistance from 2 to 10 years, which indicates little, if any, impact of plasticizer migration.

2.1.4. *Dimensional stability*

The next certification property discussed is the dimensional stability of the geomembrane (ASTM D1204, die C). This test involves heating a 254 mm square specimen in a 100°C oven for 15 min, allowing it to cool back to laboratory conditions for 1 h, then measuring the change in the linear dimensions of the specimen in the machine direction and in the transverse direction. The maximum allowable change in either dimension is 5% for the NSF-54 specification and 3% for the PGI-1104 specification, which makes the PGI-1104 specification more stringent.

Figure 11. Tear specimens after and before testing

All of the values in Figure 14 meet both specifications after 10 years of exposure, except that one of the Sample B specimens (MD/in situ moisture) exhibited a 3.3% decrease, which slightly exceeds the 3% allowed by PGI-1104. None of the zero-year data included dimensional stability data, so the results cannot be compared with the installation value.

With a few exceptions, the change in dimension in the transverse direction tends to be positive (representing an increase in the width of the specimen), whereas the change in the machine direction tends to be negative (representing a decrease in the width of the specimen). Also, for the machine direction, the magnitude of the change in dimension tends to be larger for in situ moisture condition specimens. This change is probably caused by the in situ moisture being removed during the oven drying instead of prior to the test during desiccation in the laboratory. The magnitude of the change for the desiccated specimens tends to be larger in the transverse than the machine direction. Because the in situ moisture specimens are being desiccated for the first time during the test, these results agree with the tensile results, in that behavior of the material in the machine direction is controlled more by the PVC molecules that are oriented in that direction, whereas the behavior in the transverse direction may be controlled by other factors, such as environment, moisture condition, or formulation.

2.1.5. *Low-temperature impact*

The last certification property is the low-temperature impact test (ASTM D1790). This test measures the brittleness of a geomembrane at low temperatures. The test involves folding a 51 mm × 146 mm specimen into loops, refrigerating/freezing the specimen loop at a speci-

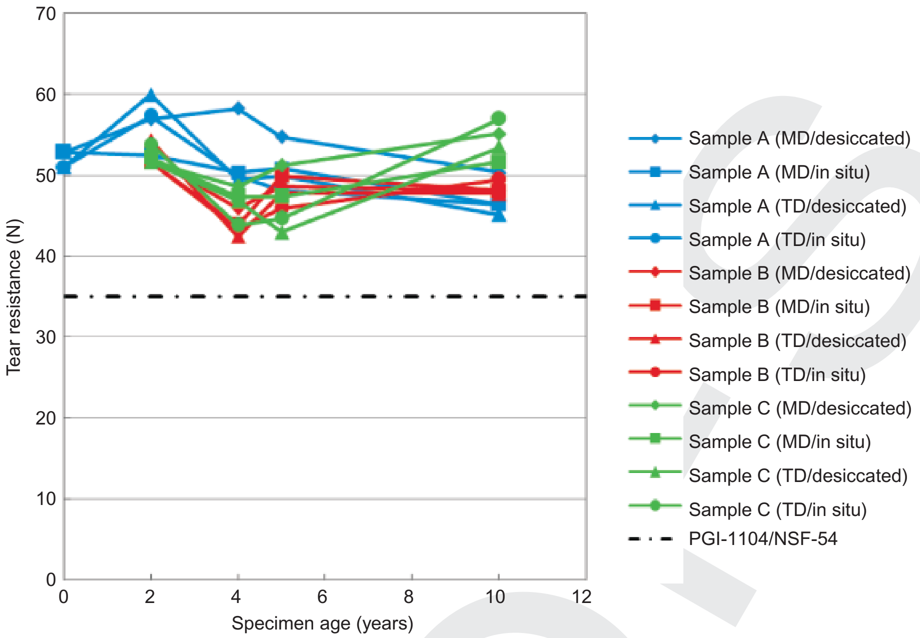

Figure 12. Tear resistance as a function of specimen age

fied temperature for 15 min, dropping a weighted hammer on the chilled loop (see Figure 15), and observing whether the specimen breaks or not. The result of a full testing program is the temperature at which a specified fraction of the specimens do not break. Because the determination of this critical or breakage temperature would require numerous batches of 12 specimens each, with each batch being tested at a different temperature as per ASTM D1790, it is common to test one set of specimens at the temperature set by the material specification and then report the percentage of the specimens that pass (i.e. that do not break). The NSF-54 specification follows the ASTM test procedure exactly, requiring 80% of the specimens to pass (not break) at −29° C, whereas the PGI-1104 specification requires only 50% of the specimens to pass (not break) at −29° C. Figure 16 shows that all of the material tested meets the PGI-1104 specification, though Manufacturer C samples from 4 years and older did not pass the NSF-54 specification.

Because of the large amount of material required for each iteration of this test, only specimens with their long dimension oriented in the transverse direction (and thus with the fracture occurring parallel to the machine direction, or the preferred orientation of the PVC molecules) were tested. As shown by the tensile and tear tests, the material is less brittle for fractures that would occur perpendicular to the MD or preferred orientation of the PVC molecules, so the test results presented herein represent a worst-case scenario.

2.2. Index properties

2.2.1. *Water extraction*

The first index property test discussed is the water extraction test (ASTM D1239). This test is performed by suspending a specimen in a 50°C water bath for 24 h, allowing it to re-acclimatise to laboratory conditions, and then measuring the percentage change in mass after the test. The maximum allowable change in mass is 0.25% under the NSF-54 specification and 0.15% under the PGI-1104 specification. Figure 17 shows that all the desiccated samples tested met both specifications after 10 years of exposure. The larger values measured for the zero-year samples suggest that any plasticizer loss that does occur happens within the first two years of exposure to the in situ environment. However, the tensile behavior discussed above suggests that the amount of observed plasticizer loss at this site has not adversely affected the performance of the material.

The results for the in situ moisture specimens are not meaningful, because the laboratory environment after they are removed from the water bath is different from the moist environment they were in before placement in the water bath. Thus the change in mass of the in situ moisture specimens reflects changes due to water extraction and desiccation after the laboratory submersion. A change in the specimen preparation procedure is necessary to use the water extraction test to evaluate samples kept at the in situ moisture condition.

2.2.2. *Volatile loss*

Similar to the water extraction test, the volatile loss test (ASTM D1203) measures a percentage change in mass due to plasticizer volatility. This test is performed by burying test specimens in layers of activated carbon, placing the buried specimens in a 70°C oven for 24 h, and then allowing the specimens to re-acclimatise to laboratory conditions for 24 h. The maximum allowable change in mass is 0.70% under both the NSF-54 and PGI-1104 specifications. As with the water extraction test, the results for the in situ moisture condition specimens are not meaningful, because they reflect desiccation of the specimens during the test procedure. All of the desiccated

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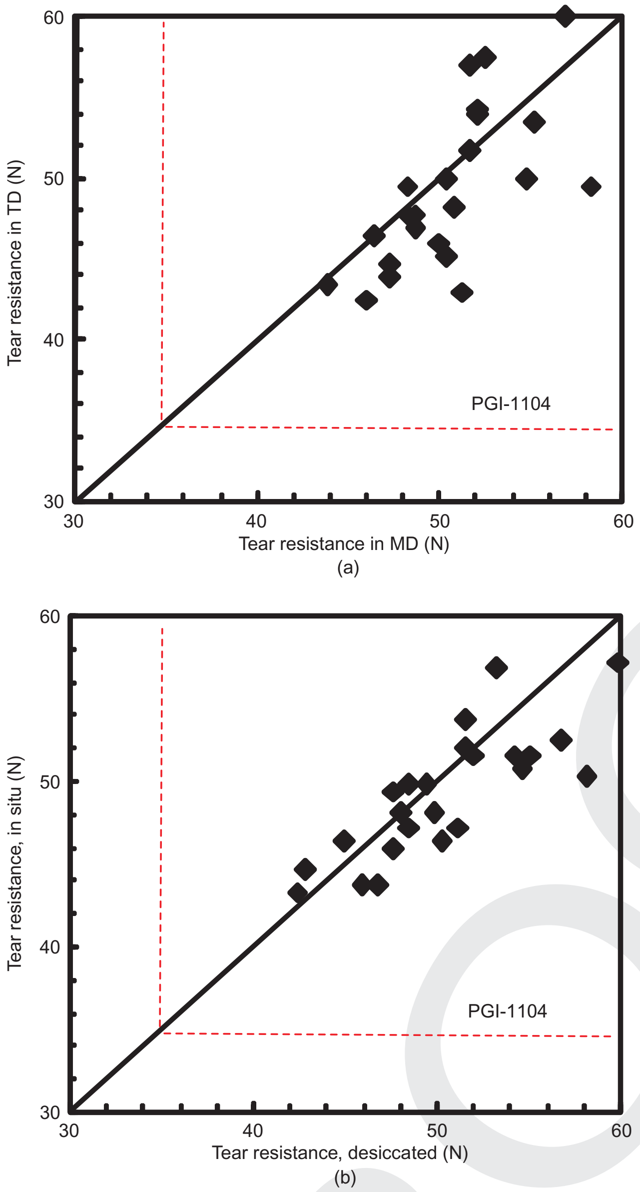

Figure 13. Effect of (a) orientation and (b) moisture condition on tear resistance

specimens in Figure 18 meet both specifications after 10 years of exposure. As with the water extraction results, the magnitude of the volume change decreases over time, which suggests that any plasticizer loss that does occur occurs only in the first few years after exposure to the in situ conditions.

2.2.3. *Hydrostatic resistance*

The final quantity measured as part of the index property tests is the hydrostatic resistance. This is the pressure required to burst a specimen of the material using a Mullen-type hydrostatic tester as per the *Standard Test Methods for Coated Fabrics* (ASTM D751). The minimum allowable hydrostatic resistance under the NSF-54 specification is 565 kPa, and that under the PGI-1104 specification is 690 kPa. Figure 19 shows that both the in situ and desiccated moisture condition specimens meet these requirements by a fair margin. Figure 20 shows higher hydrostatic resistance values for the desiccated specimens, indicating a higher strength and stiffness than the in situ specimens. This increase reflects a decrease in flexibility due to a decrease in moisture content.

To evaluate field performance, the in situ moisture specimens are more representative than the desiccated moisture condition specimen, because in this application the geomembrane is never desiccated in the field. This trend with respect to environment may appear in the hydrostatic resistance test because failure is governed only by the material itself, whereas failure in the tensile and tear tests may be influenced by the neatness (on a small scale) of the cut to create the specimen from the sample. Thus the hydrostatic resistance test may be more useful for evaluating the tensile performance of geomembranes in different environmental conditions than the tensile or tear tests mentioned previously. One limitation of ASTM D751 is that the orientation and shape of the failure are not considered or documented in this test. It may be beneficial for future testing to record the orientation and shape of the failure of these specimens when possible.

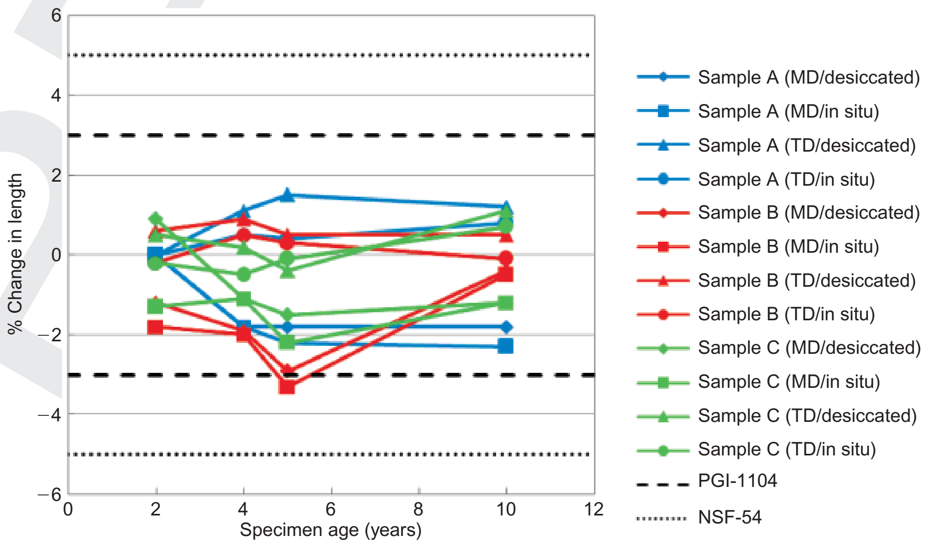

Figure 14. Results of dimensional stability tests in percentage change in length

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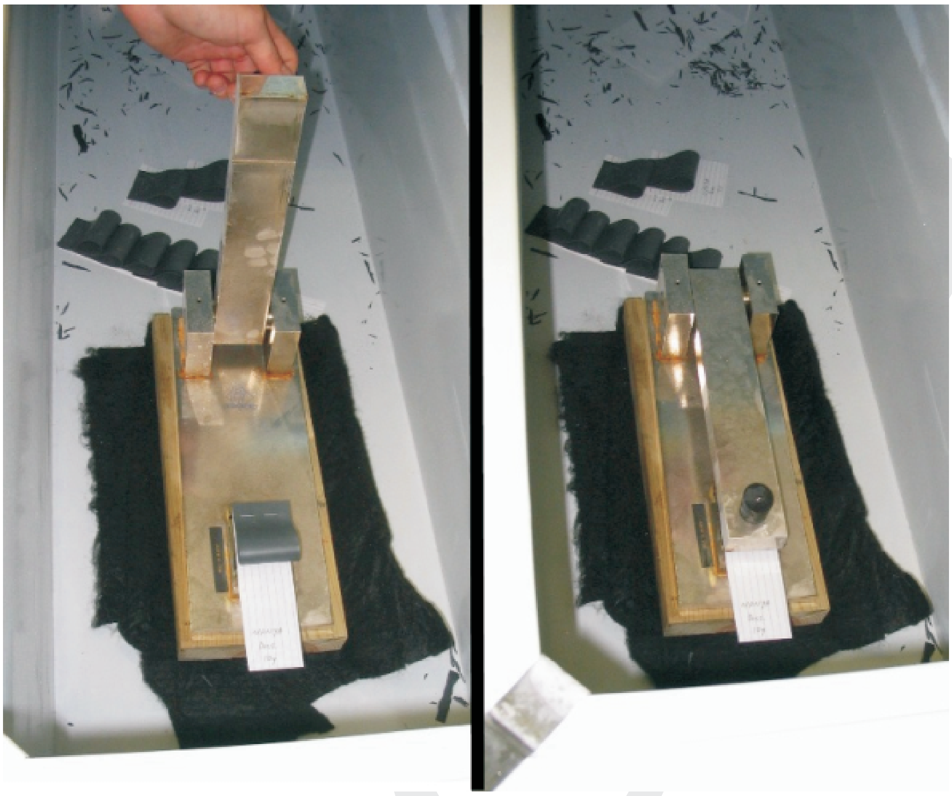

Figure 15. Low-temperature impact specimen before and after testing

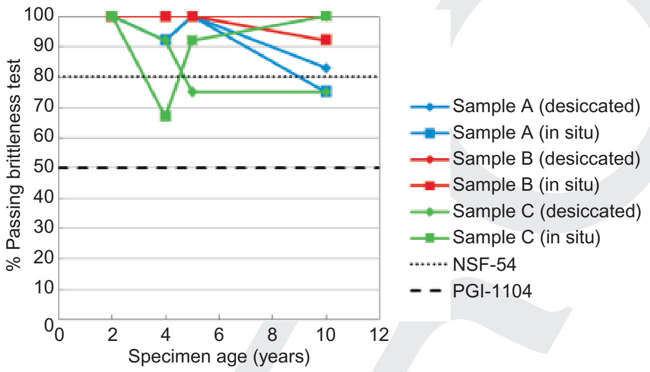

Figure 16. Percentage passing the low-temperature brittleness test at −29°C

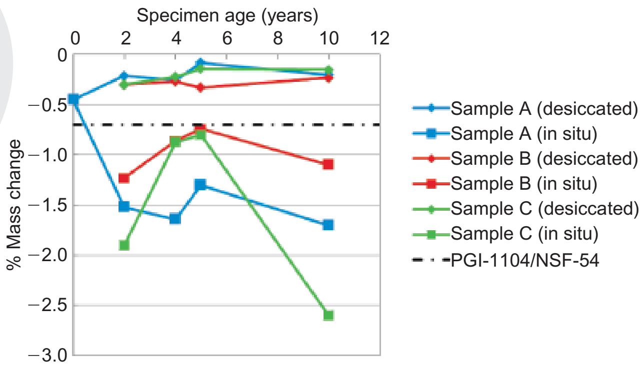

Figure 18. Percentage change in mass during volatile loss test

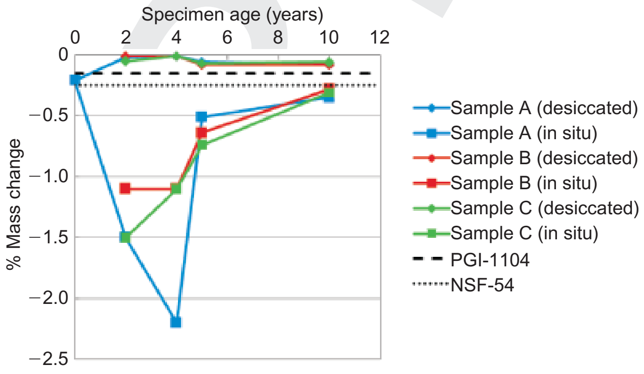

Figure 17. Percentage change in mass during water extraction test

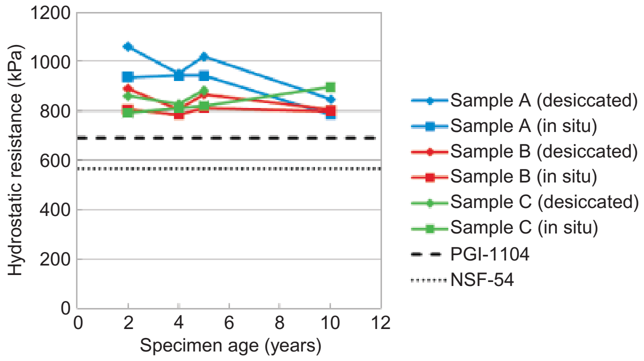

Figure 19. Hydrostatic resistance as a function of specimen age

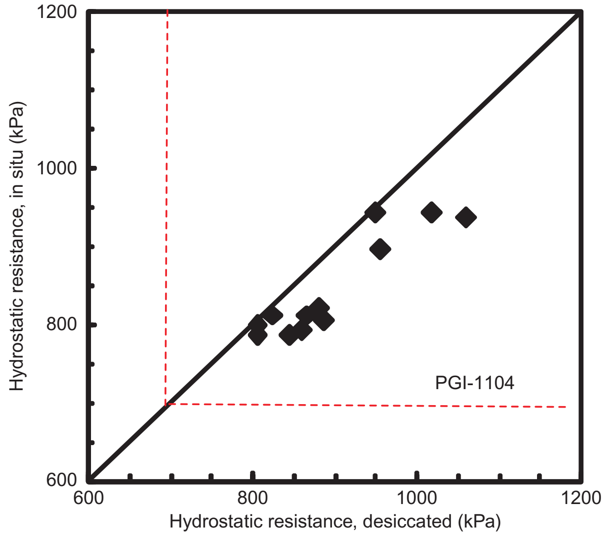

Figure 20. Effect of moisture condition on hydrostatic resistance

2.3. Seam properties

2.3.1. *Seam shear strength*

In addition to the tests measuring the physical properties of the PVC geomembrane itself, ASTM D882 was performed to measure the performance of the seams, because a seam was included in the field program. The seam shear strength is measured using the same procedure as the tensile tests described previously, at an elongation rate of 500 mm/min. From the seam sample described previously, specimens for both desiccated and in situ moisture conditions were prepared and tested. The minimum required seam shear strength under the NSF-54 specification is 9.68 kN/m, and that under the PGI-1104 specification is 10.0 kN/m. Figure 21 shows that all the seams tested exceed these requirements, and all the seams tested failed outside the bonded zone, indicating that the strength of the bonded area is greater than the strength of the geomembrane itself. Seam peel strengths could not be measured as no ‘flap’ was left to conduct a peel test, because the seams were created in a factory, so a field welder was not used.

The performance of these factory seams is important, because the geomembrane for many PVC projects is fabricated into large panels in the factory and shipped to the site for deployment, resulting in few field seams. Instead most, if not all, of the seams are created under controlled conditions, and the completed geomembrane panel is folded and shipped to the site in one piece. In general, factory seams are created by solvent or thermal welding and then tested destructively. In contrast, field seams can be non-destructively tested using air-channel testing (Stark *et al.* 2004), or destructively if desired. Thus it is important to evaluate the field performance of factory seams. Recent research shows that factory seams also perform well in thinner PVC geomembranes (0.51 mm) over even longer periods of exposure (~30 years) than studied in this project (Newman *et al.* 2004).

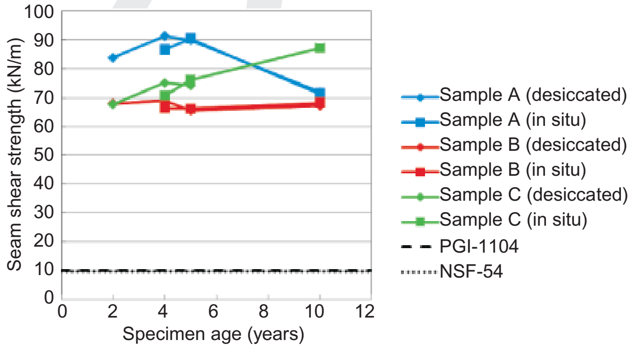

Figure 21. Seam shear strength as a function of specimen age

3. CONCLUSIONS

Most geomembrane specifications use a variety of short-term tests to predict long-term performance. Thus it is important to assess the long-term performance of geomembranes by exhuming and testing installed geomembranes after substantial field exposure. This paper describes an ongoing study of the long-term performance of PVC geomembranes in northern Minnesota. A suite of tests to investigate the certified, index, and seam properties has been conducted on samples exhumed after 10 years of service in a mine settling basin. The test results for specimens tested at the in situ moisture and laboratory desiccated moisture conditions all exceed the NSF-54 and PGI-1104 specifications except for thickness. The variability between the thickness measurements is probably due to the change in test procedures from ASTM D1593 to ASTM D1599 for measuring thickness. The specimens tested at the in situ moisture condition appear more representative of the field performance and durability than those at the desiccated moisture condition, because the geomembrane is never desiccated in this field application (settling basin).

Test results presented herein also indicate that the installed PVC geomembranes exhibit higher strength and greater stiffness in the machine direction than in the transverse direction. No clear trend in the measured properties with respect to time was observed. However, in some instances the in situ moisture condition specimens show an increase in flexibility with time, which suggests that the increased moisture content may counteract some, if not all, of the plasticizer migration that can occur in this application. In summary, the harsh environment in northern Minnesota appears to have had little effect on the engineering properties measured. However, if a thinner geomembrane is used (less than 0.76 mm) then the environment may be a larger factor in its behavior.

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PROOFS

REFERENCES

ASTM D 618. *Standard Practice for Conditioning Plastics for Testing*. ASTM International, West Conshohocken, PA, USA.

ASTM D 751. *Standard Test Methods for Coated Fabrics*. ASTM International, West Conshohocken, PA, USA.

ASTM D 882. *Standard Test Method for Tensile Properties of Thin Plastic Sheeting*. ASTM International, West Conshohocken, PA, USA.

ASTM D 1004. *Standard Test Method for Tear Resistance (Graves Tear) of Plastic Film and Sheeting*. ASTM International, West Conshohocken, PA, USA.

ASTM D 1203. *Standard Test Methods for Volatile Loss from Plastics Using Activated Carbon Methods*. ASTM International, West Conshohocken, PA, USA.

ASTM D 1204. *Standard Test Method for Linear Dimensional Changes of Nonrigid Thermoplastic Sheeting or Film at Elevated Temperature*. ASTM International, West Conshohocken, PA, USA.

ASTM D 1239. *Standard Test Method for Resistance of Plastic Films to Extraction by Chemicals*. ASTM International, West Conshohocken, PA, USA.

ASTM D 1593. *Standard Specification for Nonrigid Vinyl Chloride Plastic Film and Sheeting*. ASTM International, West Conshohocken, PA, USA.

ASTM D 1599. *Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings*. ASTM International, West Conshohocken, PA, USA.

ASTM D 1790. *Standard Test Method for Brittleness Temperature of Plastic Sheeting by Impact*. ASTM International, West Conshohocken, PA, USA.

Choi (2005). Cited in text.

Giroud, J. P. (1995). Evaluation of PVC geomembrane shrinkage due to plasticizer loss. *Geosynthetics International*, **2**, No. 6, 1099–1113.

Giroud, J. P. & Tisinger, L. G. (1995). Relationship between PVC geomembrane density and plasticizer content. *Geosynthetics International*, **2**, No. 3, 567–586.

Hillman, R. P. & Stark, T. D. (2001). Shear strength characteristics of PVC geomembrane-geosynthetic interfaces. *Geosynthetics International*, **8**, No. 2, 135–162.

Koerner, R. M., Hsuan, Y. G., Koerner, G. R. (2008). Freshwater and geosynthetics: a perfect marriage. *The 1st Pan American Geosynthetics Conference and Exhibition,* Cancun, Mexico, March. 3

NSF (1993). *International Standard 54 1993, Flexible Membrane Liners*, National Sanitation Foundation, Ann Arbor, Michigan, 30 pp.

Newman, E. J., Stark, T. D., Rohe, F. P. & Diebel, P (2004). Thirty-year durability of a 20-mil PVC geomembrane. *Journal of Vinyl and Additive Technology*, **10**, No. 4, 168–173.

PGI (PVC Geomembrane Institute) (2004). *Specifications for PVC Geomembranes*, PGI-1104, University of Illinois at Urbana-Champaign, 1 January.

Stark, T. D., Choi, H. & Thomas, R. W. (2004). Low temperature air channel testing of thermally bonded PVC geomembrane seams. *Geosynthetics International*, **11**, No. 6, 481–490.

Stark, T. D., Choi, H. & Diebel, P. (2005). Influence of plasticizer molecular weight on plasticizer retention in PVC geomembranes. *Geosynthetics International*, **12**, No. 2, 99–110. 4

Stark, T. D., Newman, E. J. & Aust, R. L. (2008). Back-analysis of a PVC geomembrane lined pond failure. *Geosynthetics International*, **15**, No. 4, 258–268.

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