DURABILITY OF FABRICATED GEOMEMBRANES: 20 YEAR UPDATE

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ABSTRACT

The long-term durability of three 0.76 mm (30 mil) thick PVC geomembranes installed in a mine settling basin in Minnesota has been investigated over a period of twenty (20) years. The tests required by the FGI-1115 PVC Geomembrane Material Specification (Formerly PGI-1104) were performed to determine whether the material still exceeded material requirements. Material testing was conducted after 2, 4, 5, 10, and 20 years of exposure to investigate the effects of contaminants and aging on the three (3) different geomembranes. Samples were tested at both the in situ moisture condition and after desiccation as required by some of the specified ASTM test methods. Moist samples exhibit greater flexibility and are more representative of in situ mechanical properties than desiccated samples. After twenty (20) years of exposure there has been no significant degradation in the properties of the geomembranes and they mostly exceed current and past material specification, e.g., NSF-54 and FGI-1115, values. Additional testing will be conducted after 25 and 30 years of exposure.

INTRODUCTION

The Fabricated Geomembrane Institute (FGI), formerly the PVC Geomembrane Institute (PGI), in collaboration with the Minnesota Department of Natural Resources (MN DNR) has been conducting a study to assess the long-term durability of PVC geomembranes. Samples of three (3) different 0.76 mm (30 mil) thick PVC geomembranes were placed at the bottom of a mine settling basin in Hibbing, Minnesota on October 1995 with the intention of extracting samples for laboratory testing after 2, 4, 5, 10, 20, 25, and 30 years.

The water in the mine settling basin is discharged from a water treatment system which uses magnesium hydroxide to neutralize acidic drainage from sulfidic rock weathering tests nearby to simulate weathering and treatment of waste rock piles. The basin has a capacity of approximately 2.27 million liters (600,000 gallons) and the water chemistry varies due to climatic variation, i.e., precipitation and evaporation. Since 1996 the range of measured fluid parameters for the water in the settling basin are: pH 7.12 to 9.79, conductivity 30 to 1675 μS/cm, nickel...
concentration of 0.05 to 0.4 mg/L, copper of 0.001 to 0.5 mg/L, cobalt of 0.001 to 0.1 mg/L, zinc of 0.001 to 1.34 mg/L, sulfate concentration of 30.4 to 421.0 mg/L, and mercury concentration from 3.30 to 4.03 ng/L.

This ongoing research project is investigating the 30-year durability of PVC geomembranes and PVC chemical fusion and thermally welded seams. Results from the first ten (10) years of this investigation are presented in Newman and Stark (2009) and this paper presents the results from testing of the twenty (20) year old samples.

Three (3) 0.76 mm (30 mil) thick PVC geomembranes from three different manufacturers were placed at the bottom of a double-lined water treatment mine related settling basin at a MN DNR field research site in Hibbing, Minnesota in October 1995. The extreme weather fluctuations and harsh winters with annual freeze/thaw cycles provided an excellent environment to test the durability of these materials, which are being used to contain mining related contaminants.

![Figure 1](image)

**Figure 1:** Photographs show Steve Koski (L) and Austin Dusek (R) both with the Minnesota DNR and T.D. Stark with the University of Illinois at Urbana-Champaign: (a) uncovering one of the PVC geomembrane samples cut from the longer sample that still remains on the bottom of the sedimentation basin under about 150 mm (six inches) of sand cover and (b) the individuals holding the geomembrane sample cut from the still buried sample before being rolled up for transportation.

**LABORATORY TESTING**

Nine different laboratory tests were conducted on each exhumed material along both the machine (MD) and transverse (TD) directions of the geomembrane: (1) thickness (ASTM D5199), (2) tensile strength at break, elongation at break and strength at 100% strain (ASTM D882 Method A), (3) tear strength (ASTM D1004), (4) dimensional stability (ASTM D1204), (5) low temperature impact (ASTM D1790), (6) water extraction (ASTM D1239), (6) volatile loss (ASTM D1203), (7) hydrostatic resistance (ASTM D751), (8) seam shear strength (ASTM D882 Method A), and (9) seam peel strength (ASTM D882). Because of space constraints, only the results from the following tests are presented herein: (1) thickness, ASTM D5199; (2) tensile strength, ASTM D882, Method A; (3) tear resistance, ASTM D1004; (4) dimensional stability ASTM D1204; (5)
low temperature impact, ASTM D1790; (7) hydrostatic resistance, ASTM D751; and (8) seam shear strength, ASTM D882 Method A.

ASTM D618 recommends desiccation of the samples prior to testing by letting samples acclimate for at least 40 hours at room temperature, which is not representative of the material properties mobilized in the field. To investigate this effect, all of the testing was conducted on specimens as close to field moisture conditions as possible and after at least a week of desiccation at room temperature in accordance with ASTM D618. Desiccated samples were routinely weighed until the mass remained constant to indicate that the sample reached equilibrium with the laboratory conditions.

New testing standards have been adopted since the beginning of this investigation in 1995. In particular: ASTM D7176-06 (2011) Standard Specification for Non-Reinforced Polyvinyl Chloride (PVC) Geomembranes Used in Buried Applications and ASTM D7408-12 Standard Specification for Non Reinforced PVC (Polyvinyl Chloride) Geomembrane Seams have been adopted. Because these test methods were not available in 1995, older test methods were used in this stage of the investigation to compare the evolution of material properties with time. The properties determined by these tests were then compared against reference values from Guideline #54 from the National Sanitation Foundation (NSF-54) and FGI 1115 (formerly PGI 1104) to evaluate material performance after exposure. The outdated NSF-54 specification was included because it was the active and the industry standard in 1995 when the geomembranes were manufactured and installed in the mine settling basin.

Certified Properties

**Figure 2** shows the variation of geomembrane thickness over time. For the first two years of this investigation geomembrane thickness was determined using ASTM D1593, which uses the specific gravity and specimen area to calculate thickness. For subsequent testing, geomembrane thickness was measured directly in accordance with ASTM D5199 where specimen thickness is measured directly with a dial gauge with a weighted presser foot.

The geomembrane specimens generally increased in thickness during the first five (5) years of exposure and then the thickness generally decreased. Newman and Stark (2009) suggest that the different trends before and after five years could be due to the different testing methods. The desiccated specimens are thinner than the in situ ones due to the loss of the absorbed moisture. The FGI-1115 specification allows for variations of up to 0.04 mm for a 0.76 mm thick PVC geomembrane. The dashed line in **Figure 2** corresponds to a thickness of 0.76 mm (30 mil). Geomembrane Samples B and C have remained within this range, but since the fifth year of exposure Sample A has shown thicknesses greater than 0.80 mm.

The tensile properties of the geomembranes were evaluated using ASTM D882 *Standard Test Method for Tensile Properties of Thin Plastic Sheeting*. Test specimens with dimensions of 25.4 mm by 152.4 mm (1 in. by 6 in.) were cut using a custom steel die along the machine and transverse directions of the exhumed samples. These specimens were tested using an initial grip separation of 50.8 mm (2 in.) and tensioned at a rate of 500 mm/min (20 in./min). Three (3) measurements were made on these samples: (1) tensile break strength, (2) secant modulus at 100% strain and (3) elongation at break. The tensiometer used in this investigation does not have data acquisition capabilities so manual measurements were made to determine the strength at 100% strain and the elongation at break.
Figure 2: Geomembrane specimen thickness as a function of age.

Figure 3 presents the tensile break strength as a function of specimen age. Figure 3 shows there is great variability in the tensile break strengths determined at different times during this investigation. As a result, there is no general trend across the three geomembrane materials included in this study. Plasticizer migration due to the 20 years of exposure in the treated mine water has not resulted in a general increase in the tensile break strength due to an increase in stiffness. After 20 years there has been no such trend, with the measured tensile break strengths both increasing and decreasing with exposure time or specimen age.

The minimum tensile break strengths required by NSF-54 and FGI-1115 are 12.1 kN/m and 12.8 kN/m, respectively. With the exception of Sample C during the five (5) year testing, all of the geomembrane materials irrespective of specimen age, specimen direction (MD v. TD), and sample desiccation are still compliant with both material specifications. Sample C exhibited a large decrease in the tensile break strength in the past ten (10) years but the lowest strength is 13.2 kN/m, which still exceeds the specifications. In general, the tensile break strength tend to be higher in the MD than the TD due to the orientation of PVC molecules during manufacturing in the MD.

The calculated values of secant modulus at 100% strain from the tensile tests are plotted in Figure 4. The secant modulus is the tensile strength mobilized for a given strain, e.g., 100%, which is used in the absence of a tensile stress-axial strain relationship that is required to determine the modulus of elasticity. The secant modulus provides an indication of the stiffness of the geomembrane with time. A high secant modulus indicates a stiffer material. If the secant modulus increases with time, it can be an indication that the PVC geomembrane has lost some plasticizer because the material is becoming stiffer.
Measurements were made of the force required to double the length of the specimen, which corresponds to 100% strain. As is the case with the tensile break strength, there is no clear trend between secant modulus and specimen age. However, specimen preparation did have a significant impact on the measured secant modulus. For the most part, the desiccated specimens resulted in
higher values of secant modulus, which is indicative of a stiffer material than the in situ moisture specimens. The in situ moisture specimens yielded lower moduli and greater flexibility, which is more representative of the field behavior of the geomembranes.

The NSF-54 specification requires a secant modulus of 5.3 kN/m while the FGI-1115 specification requires 5.6 kN/m. For the first ten (10) years of exposure all of the geomembranes exceeded these requirements. However, after 20 years of exposure the specimens at the in situ moisture condition for Sample B dropped to 4.75 kN/m (MD) and 5.03 kN/m (TD), which indicates that the material is getting softer with time. This trend is confusing because it is frequently believed that PVC geomembranes lose plasticizer and thus should become stiffer with time. This trend was not observed in the desiccated specimens as shown by the stiffness of Sample B increasing with time since the testing reported in Newman and Stark (2009). The secant modulus values reinforce the importance of testing buried geomembranes at their natural moisture content instead of desiccated specimens.

The elongation at break was also measured for all of the exhumed samples and is plotted in Figure 5. All of the samples still comply with both the NSF-54 and FGI-1115 specifications, which requires a minimum elongations at break of 325% and 380%, respectively. Samples along the transverse direction (TD) displayed a little higher elongation at break than the MD. The twenty (20) year specimens show greater elongation at break for the in situ moisture condition with no exception, but this trend was not always observed in previous testing intervals. Since the ten (10) year testing, values of elongation at break have decreased for all of the specimens with values for desiccated Sample C nearing the minimum FGI-1115 specification of 380%. The in situ Sample C testing resulted in average elongations of 441% (MD) and 443% (TD), meaning that the desiccated results can be misleading and suggest that the geomembrane is less flexible than it is at field conditions or moisture.

The geomembrane tear strength was measured using ASTM D1004, which is known as the Graves Tear Test. The tear strength is governed by the transverse direction (TD) because it is perpendicular to the PVC molecular strands in the MD of the geomembrane. Test specimens were cut from the exhumed samples using a special die to create a notched strip. The notch creates a plane of weakness at the center of the specimen along which tearing is initiated. Specimens are failed at a constant elongation rate of 51 mm/minute (2 inches/minute) and the peak tear resistance is recorded. Ten (10) desiccated and ten (10) in situ specimens in the MD and TD directions were tested from each exhumed sample and the results are plotted in Figure 6. All specimens have consistently exceeded the NSF-54 and FGI-1115 specifications for tear resistance, which is 35 N for both specifications.

As expected, the tear resistance is generally higher along the MD because the direction of tearing is perpendicular to the general orientation of the PVC molecules. Desiccated specimens also tended to yield a greater tear resistance due to the increased stiffness observed in the tensile tests described above. Figure 6 shows the ten (10) year testing of desiccated Sample A yielded a large increase in tear resistance but this trend is not present for the in situ moisture specimens.
Figure 5: Elongation at break as a function of time.

Figure 6: Tear resistance as a function of time.

The results of the dimensional stability tests over time are presented in **Figure 7**. This testing was performed in accordance with ASTM D1204 *Standard Test Method for Linear Dimensional Changes of Nonrigid Thermoplastic Sheeting or Film at Elevated Temperature*. The dimensional stability test involves measuring the linear dimensions of the samples along the machine (MD) and
transverse (TD) directions before and after 15 minutes in an oven at 100 °C. After exposure, the samples are allowed to re-acclimate to room temperature for two (2) hours before measurements are taken.

Four (4) 25 cm x 25 cm squares were cut from each of the three exhumed geomembrane samples (see Figure 1). Two samples from each exhumed geomembrane were allowed to acclimate to room temperature for a week and the other two samples from each exhumed geomembrane were either immediately tested or sealed in bags and stored in a moisture room to yield results at the field moisture condition.

The NSF-54 specification allows for a maximum of ±5% change in either the MD or TD directions, while FGI-1115 allows only a ±3% change in either direction. With the exception of Sample B tested at insitu moist conditions after five years of exposure, all three of the exhumed geomembranes were consistently within the required specification during the 20 years of exposure. The non-compliant Sample B at five (5) years of exposure could be the result of variations within the manufactured roll. Generally, the geomembranes experienced positive changes after heating, which indicates extension along the transverse direction and contraction along the machine direction due to thermal effects on the PVC molecules. From Figure 7 no obvious trend was observed for samples that were desiccated. However, the data does show that moisture was removed during the exposure period and re-acclimation in the laboratory due to evaporation.

![Figure 7: Dimensional stability as a function of age.](image)

One geomembrane property that underwent a significant change since the ten (10) year testing performed in 2005 is the resistance to low temperature impact at -29°C. This test is conducted in accordance with ASTM D1790 by introducing folded strips of the geomembrane into a freezer and allowing it to acclimate to -29 °C for 15 minutes. A hammer is then dropped on the fold in the geomembrane. If the test specimen does not shatter at the fold, it passes the test. As a result, this test is also referred to as the brittleness test. As expected, Samples A and B show better
performance at the in situ moisture condition than in the desiccated condition. The specimens of
Samples A and B at the in situ moisture condition exceed the FGI and NSF specifications, which
require 50% and 80% passage, respectively, as shown in Figure 8. Samples A and B under in
situ moisture test conditions performed better than the desiccated specimens but both sets of
specimens pass or are in agreement with the FGI specification. In the case of Sample A, desiccating
the specimens prior to testing as specified in ASTM D-1790 resulted in only 50% passing the
requirement, while 85% of the in situ moisture samples passed.

Figure 8 also shows that specimens from the 20 year exhumed Sample C did not pass at
the in situ moisture condition and 98% of the desiccated specimens also did not pass the FGI
specification. Both of these results are well below the 50% required for passing the FGI
specification. These tests were conducted twice with samples taken from different parts of the 20
year exhumed geomembrane to confirm the results. The increased failure rate could be related to
the decrease in tensile break strength and percent elongation at break described above, which is
indicative of decreased flexibility and potentially some plasticizer migration. However, the
geomembrane was still quite flexible and easily rolled into a tight roll for sealing and shipping
after being exhumed. It will be interesting to test the twenty-five (25) year specimens for this
geomembrane in 2020.

![Figure 8: Low temperature impact at -29 °C or brittleness as a function of times.](image)
**Hydrostatic Resistance**

The changes in hydrostatic resistance with time were measured using the test method ASTM D751 Procedure A- Mullen Burst Type. A Mullen Burst hydrostatic device was used to burst ten (10) desiccated and ten (10) in situ moisture specimens of each exhumed geomembrane. **Figure 9** shows that there has been no significant degradation in the hydrostatic resistance after twenty (20) years of exposure. All of the geomembranes regardless of sample preparation, i.e., in situ moisture or desiccated, exceed the NSF-54 and FGI-1115 specifications of 565 kPa and 690 kPa, respectively.

The desiccation procedure recommended by ASTM results in higher values of hydrostatic resistance than the specimens at the in situ moisture condition. For Samples B and C the difference is slight, but for Sample A there is a noticeable increase in burst strength for the desiccated specimens (855 kPa to 1012 kPa). This is due to the greater flexibility of the in situ moisture then desiccated specimens, which is also reflected in the elongation at break and secant modulus described above.

**Figure 9** also shows little variability in the measured hydrostatic resistance values even after twenty (20) years of exposure. Due to the lower variability in hydrostatic resistance than the various tensile test measurements described above, Newman and Stark (2009) recommend the use of hydrostatic resistance testing to evaluate the in situ performance of PVC geomembranes. For example, the tensile testing on the twenty (20) year exhumed samples show several instances where the measured values approach or fall below NSF-54 and/or FGI-1115 specifications but the hydrostatic testing yielded consistent and acceptable values.

![Figure 9: Hydrostatic resistance as a function of time.](image-url)
Seam Shear Strength

The results from shear strength testing of the seam in each of the three PVC geomembrane samples are presented in Figure 10. Geomembrane Sample A has a thermal or hot wedge seam while Samples B and C have a chemical solvent seam.

The seam tests were conducted on specimens with a width and length of 25 mm x 150 mm that were cut with a die so the seam is at the middle of the test strip. These strips were tested in accordance with ASTM D882 at an elongation rate of 500 mm/minute. The minimum strength required by NSF-54 and FGI-1115 is 9.68 kN/m and 10 kN/m, respectively. After twenty (20) years of exposure the seams in all three of the geomembranes are exceeding required specifications. During testing, all of the seam specimens failed either at the edge of the bonded area of the seam or at the grip in the tensiometer. This indicates that even after twenty (20) years of exposure, factory fabricated seams are stronger than the parent material. Because the seam specimens failed outside of the seam, the seam shear strengths follow the general trends observed in the tensile break strength tests.

When the chemical seams were created, no loose flap of material was left so seam peel strength tests could not be performed. The seam created using a hot wedge welder for Sample A does have loose flaps so the seam peel strength could be measured using both the desiccated and in situ moisture specimens. The desiccated and in situ moisture specimens exhibited seam peel strengths of 4.8 kN/m and 6.2 kN/m, respectively, both of which are well above the FGI-1115 requirement of 2.6 kN/m.

![Figure 10: Seam shear strength as a function of time.](image-url)
SUMMARY

Testing of three (3) different 0.76 mm (30 mil) thick PVC geomembranes exhumed after twenty (20) years of exposure to a variety of fluids in the bottom of a mine settling basin in Hibbing, Minnesota leads to the following observations:

- Laboratory test results show that the material properties of three different PVC geomembranes exceed the original NSF-54 specification in effect at the time of manufacture and the current FGI-1115 PVC geomembrane specification. Therefore, there has been no adverse effect on the performance of these geomembranes after twenty (20) years of exposure.
- Specimens tested at the in situ moisture condition are more representative of the field conditions, performance, and durability than a desiccated condition which is required by a variety of ASTM test methods. Desiccation of exhumed specimens prior to laboratory testing tends to make the geomembranes stiffer and more brittle than actually present in the field.
- After twenty (20) years of exposure in this harsh environment in northern Minnesota, some of the index properties are changing and moving towards the specified limit. For example, Geomembrane Sample C failed the low temperature impact test after twenty (20) years even though the sample is still quite flexible, as evidenced by the results of the tensile testing.
- New samples of these three geomembranes will be exhumed in 2020 and 2025 to evaluate their performance after 25 and 30 years of exposure, respectively. Eight (8) additional geomembrane materials, e.g., HDPE, LLDPE, fPP, EIA, PVC, etc., were added to the bottom of this mine settling basin in 2018 to broaden the scope of the study. Samples of these new materials also will be exhumed in 2020.

REFERENCE

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