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# PVC aquaculture liners stand the test of time

## After three decades of performance, exhumed geomembrane retains strength and flexibility.

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In 1971, 20 circular aquaculture ponds were constructed at the W.K. Kellogg Biological Research Station at the Michigan State University facility in Hickory Corners, Mich., under a grant from the National Science Foundation. Eighteen of the ponds are for experimental purposes and two are for storage purposes. The ponds were allowed to colonize naturally with flora and fauna from surrounding lakes, and within a few years the experimental ponds closely resembled natural ecosystems. These conditions provided the opportunity to conduct a number of significant experiments on species interactions and habitat selection in fishes. Additional information on the W.K. Kellogg Biological Research Station can be found at its website: www.kbs.msu.edu/Research_Facilities/Pond_Lab/Overview.htm.

The 100-ft. (30.5-m) -diameter research ponds were lined using 20-mil-thick fish-grade PVC geomembrane. A fish-grade PVC geomembrane is specially formulated to promote aquatic life through the omission of biocides, which may leach out over time from the basic PVC geomembrane formulation. The basic formulation of a PVC geomembrane corresponds to 60-65% PVC resin, 32-38% plasticizer, 5-8% stabilizers and additives, and 0.5-1% pigment (Diebel 2000). The ponds are 8 ft. (2.4 m) deep , with side slopes of 3H:1V. After installation, each PVC geomembrane was covered with 1 ft. (0.3 m) of sandy soil.

Over time, the ponds became congested with dense, persistent stands of cattails and other vegetation (**Photo 1**). These conditions made many types of experiments impossible. Thus, in preparation for new aquaculture experiments, nine of the ponds were cleared and re-lined in September 2000. This provided a unique opportunity to exhume 29-year-old PVC geomembranes and evaluate their engineering properties. It is important to note that none of the ponds leaked or exhibited any problems during the 29 years of service. The nine ponds were re-lined with 20-mil PVC fish-grade geomembrane liner fabricated in circular panels. Each 11,060-ft.$^2$ (1,028-m$^2$) panel was made of material supplied by Geon Inc. of Burlington, N.J. The new circular panels were fabricated by Environmental Protection Inc., Mancelona, Mich. Woolf Excavating, Kalamazoo, Mich., installed the one-piece liners in ponds 4 through 8, 10, 16, 17 and 18.

***Photo 1**: Willow tree and cattails being removed for geomembrane exhumation.*

On September 13, 2000, a research assistant from the University of Illinois at Urbana-Champaign (UIUC) removed samples of the 29-year-old, 20-mil-thick PVC geomembrane from the ponds. The samples were exhumed from three locations: (1) from the side slopes above the waterline, (2) from the side slopes below the waterline and under the cattails, and (3) from the bottom of the ponds. The samples were sealed in large plastic bags to minimize moisture loss and were driven to the UIUC. Some of the samples were then shipped to TRI/Environmental, Austin, Texas, for comparison testing.

## Observations of geomembrane during excavation

All of the samples removed from the pond were soft and flexible, which is evident from their elongation at break values, presented subsequently, which satisfy specification values. The flexibility of the 29-year-old material also is illustrated by the photographs of a specimen of the sideslope material from below the water line before and during tensile testing (**Photo 2**). It can be seen that the specimen is undergoing substantial elongation during testing. Material removed from the bottom of the pond was softer to the hand than the material from above the water line. Once the samples were desiccated in accordance with ASTM test procedures, the samples were somewhat less flexible, which strongly suggests that exhumed material should be tested in the *in situ* condition, i.e., without desiccation, as required by ASTM Standard Test Methods to properly assess the *in situ* properties.

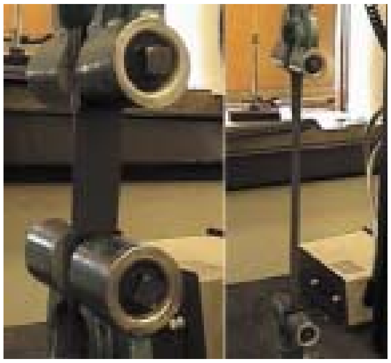

***Photo 2**: Exhumed PVC before and during tensile testing.*

At the center of each pond, an inlet/outlet structure was constructed (**Photo 3**). This structure consisted of a concrete slab, approximately 2.5 ft. x 2.5 ft. (0.76 m x 0.76 m), whose top was level with the liner subgrade. The liner was placed over the concrete, sealed with butyl mastic, and fastened to the concrete using 2-in.-by-4-in. (5-cm-by-10.1-cm) redwood batten strips and concrete nails. This structure and the batten performed well over the nearly 30 years, as indicated by no discoloration of the soil under the PVC geomembrane or around the structure. These observations also indicate that there was little, if any, leakage through the liner in the vicinity of the inlet/outlet structure. In addition, the mastic was soft and flexible after nearly 30 years, which resulted in an effective seal around the nails.

***Photo 3**: Redwood strips surrounding inlet/outlet structure at bottom of a pond.*

## Root penetration and microorganisms

One of the most important aspects of this forensic study was the effect of root penetration and microorganisms on the PVC geomembranes. As mentioned previously, the pond was overgrown with vegetation, which prompted the excavation and pond re-lining. Each of the ponds had a large amount of cattails around the perimeter of the pond (**Photo 1**) and in the middle of the pond. As the bulldozer removed the soil from the top of the geomembrane under the cattail area, observations were made of the root zone of the cattails. These cattails produced one root stalk about 0.75 in. to 1.25 in. (1.9 cm to 3.17 cm) in diameter, with a mass of smaller roots around the main root. The root length was approximately 1 to 3 ft. (0.3 m to 0.9 m). All roots of the cattails grew down to the PVC geomembrane and then grew horizontally along the top surface of the geomembrane. No evidence of roots penetrating the 20-mil-thick geomembranes was found during field inspection or after holding the geomembrane over a light source.

In one of the ponds a small willow tree was growing about 5 ft. (1.5 m) down-slope of the anchor trench but above the water level. The willow tree was 12 to 15-ft. (3.66 to 4.57-m) tall and had a trunk of 6 to 8 in. (15.2 to 20.3 cm) diameter (**Photo 1**). As the bulldozer operator cleared the soil from the sides of the tree, it was observed that the large tree roots also grew down to the geomembrane, then turned and traveled along the surface of the geomembrane. The main tree roots were 3 to 5 ft. (0.9 to 1.5 m) long, with some smaller roots extending up to 7 ft. (2.1 m) from the tree trunk. When the dozer pushed the tree over, it slid down the geomembrane to the bottom of the pond, leaving the geomembrane intact. Again no evidence of root penetration was found during field inspection or after holding the geomembrane from the vicinity of the willow tree over a light source. These observations are especially significant because the geomembrane is only 20-mil thick.

The fact that holes were not observed either in the field or in the laboratory in front of a light source also suggests that the geomembrane resisted biological attack from microorganisms. In addition, there was no surfacial damage to the geomembrane to indicate microorganism attack. This is significant because the experiments conducted in the ponds introduced many types of microorganisms inside the ponds. These qualitative data suggest that there has been no detrimental effect on the geomembrane from root penetration or microorganisms since it was installed in 1971.

## Test results on exhumed geomembrane

Samples exhumed from above and below the water line were tested at the UIUC to evaluate the effect of submergence on their engineering properties. Only samples exhumed from below the water line were tested at TRI/Environmental. Samples from each location were tested in both the machine (MD) and transverse (TD) directions. The test results are compared to the National Sanitation Foundation Specification, NSF-54, to quantify the changes in material and seam properties of the PVC geomembranes over the 29 years and 8 months of service. NSF-54 was the applicable standard in force in 1971 when the ponds were constructed and was used for comparison purposes because pieces of the original material were unavailable for testing. To further evaluate the performance of the exhumed geomembrane, the corresponding values of the PGI-1197 specification are also shown for each test. PGI-1197, which became effective January 1, 1997, was developed by the PVC Geomembrane Institute (PGI) to fill the void left by the obsolescence of NSF-54.

Some of the samples from each location were cleaned and allowed to acclimate and desiccate in the lab for 40 hours according to the applicable ASTM standard test methods. Other samples from each location were tested after being stored in a moist room until testing, in order to prevent desiccation. This anti-desiccation procedure was implemented to provide a better estimate of the *in situ* properties. Non-desiccated material provides a better simulation of the field moisture condition, which results in a more flexible material and better engineering properties. The test results from the non-desiccated samples are being reported elsewhere due to space constraints and because they yield more favorable results than the desiccated samples concerning the long-term behavior of PVC geomembranes. As

| Test | Orientation | NSF-54 | PGI-1197 | UIUC | TRI | Test Method |
|---|---|---|---|---|---|---|
| Tensile Properties (Break Strength, lbs/in.) | MD<br>TD | 46<br>46 | 48<br>48 | 72<br>59 | 62<br>60 | ASTM D-882, Method A |
| Tensile Properties (Elongation at Break, %) | MD<br>TD | 325<br>325 | 350<br>350 | 352<br>355 | 368<br>447 | ASTM D-882, Method A |
| Tensile Properties (Secant Modulus at 100% Strain, lbs/in.) | MD<br>TD | 20<br>20 | 23<br>23 | 56<br>49 | Not Tested<br>Not Tested | ASTM D-882, Method A |
| Tear Resistance (lbs.) (tensile strength with a notched specimen) | MD<br>TD | 6<br>6 | 6.5<br>6.5 | 13.3<br>12.1 | 8.4<br>8.2 | ASTM D-1004 |
| Seam Properties (Bonded Shear Strength, lbs/in.) | | 36.8 | 38.4 | 51.8 | Not Tested | ASTM D-882 |
| Hydrostatic Resistance (psi) | | 60 | 68 | 149.3 | 103 | ASTM D-751 (A) |
| Thickness (minimum, mils) | | 19 | 19 | 18.9 | 20.5 | ASTM D-5199, ASTM D-1593 |
| Dimensional Stability (% change) (Indicates material uniformity by measuring changes in linear dimensions from exposure to elevated temperatures) | MD<br>TD | ±5<br>±5 | ±5<br>±5 | -4.70<br>-1.37 | -2.02<br>0.87 | ASTM D-1790 (100C, 0.25 hr) |
| Water Extraction (% change) (measures plasticizer retention in water) | | -0.25 | -0.15 | 0.09 | 0.04 | ASTM D-3080 |
| Volatile Loss (% loss) (measures plasticizer retention in activated carbon) | | 0.9 | 0.9 | 0.01 | 0.26 | ASTM D-1203 |
| Low Temperature Brittleness (% passing at -26C ( -14.8F)) (Indicates plasticizer effectiveness by determining geomembrane tendency for brittle failure under a given impact condition) | | 80 | 80 | 90 | 100 | ASTM D-1790 |

***Table 1**: Test results for material exhumed from below water level and desiccated in accordance with corresponding ASTM test method.*

a result, the desiccated test results presented herein present a worst-case scenario for the engineering properties of the *in situ* material. However, it will be shown that the measured properties of the desiccated samples still exceed the requirements of the NSF-54 and PGI-1197 specifications.

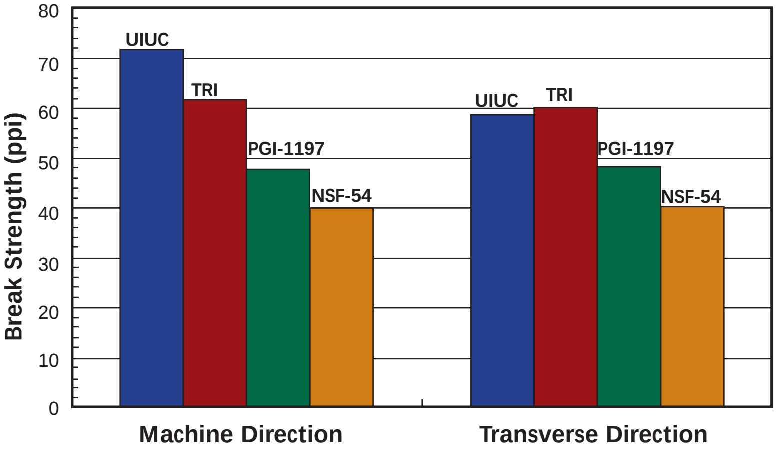

***Figure 1***: *Tensile break strengths in the machine and transverse directions compared to NSF-54 and PGI-1197 specifications.*

The test results shown in **Table 1** are for material that was obtained from near the bottom of the pond. **Table 1** shows agreement between the test results obtained from the testing at the UIUC and TRI/Environmental (TRI). More importantly, the results show that the 29-year-old material properties exceed the NSF-54 required values and the more restrictive PGI-1197 values. For example, the tensile property data show a sufficient percent elongation at break (greater than 350%) in both the machine and transverse directions, which indicates that the material retained its flexibility. Samples were also tested to determine the secant modulus of elasticity, a measure of geomembrane flexibility, which is calculated using the load required to achieve 100% strain. A low secant modulus indicates a softer, more elastic and flexible material, while a high modulus number indicates a stiffer material. The secant modulus is approximately two times higher than the recommended values, which indicates some hardening over 29 years. However, some of this hardening may be attributable to the desiccation of the material prior to testing. The hardening also may have contributed to the tensile break strength values comfortably exceeding the specification values (**Figure 1**).

The results of the water-extraction and volatile-loss tests also confirm sufficient plasticizer retention after 29 years. One interesting result from this testing is the water extraction data. The UIUC data indicate a gain in water during the test, as did the TRI/Environmental, albeit to a lesser degree. This may be attributed to desiccation of the material prior to testing, which reinforces that exhumed specimens should be tested at *in situ* moisture conditions. The factory seams were created using a solvent and the performance of the seams over 29 years was of particular interest. It can be seen from **Table 1** that the bonded shear strength exceeded the recommended NSF-54 and PGI-1197 values. Peel tests of the seams were not conducted because the solvent seams did not have a “flap” to permit peel testing. TRI/Environmental did not test a seam because the material that was shipped did not contain a seam.

Plasticizer retention is more difficult in an aquatic vs. non-aquatic environment because as the water circulates, it provides a continuous opportunity for plasticizer migration unlike a non-aquatic environment. In addition, the thinner the sheet, the larger the impact of surfacial plasticizer loss will be on the measured properties. Thus the percentage change in engineering properties can be greater for a 20-mil- vs. 30-mil-thick geomembrane. Therefore, it is significant that test results on a 20-mil-thick PVC geomembrane after nearly 30 years in an aquatic environment still exceeded the NSF-54 and PGI-1197 recommended values. This indicates that the formulation was proper and the plasticizer was sufficiently retained even in the aquatic environment.

Material from above the water line was also tested and the results are shown in **Table 2**. Above the water line, i.e., in a non-aquatic environment, it is anticipated that plasticizer retention would be higher than below the water line, i.e., in an aquatic environment. This is caused by water not being continuously available to remove some of the plasticizer. Evidence of greater plasticizer retention can be seen in comparing the tensile properties in **Tables 1** and **2**. For example, the break strength is lower for the material above the water line, indicating a slightly softer material than below the water line. This additional plasticizer retention above the water line is also reflected in the larger value of percent elongation at break (369% vs. 352%) and lower value of secant modulus (48 ppi vs. 56 ppi) than the below-water-line material. This suggests that the material is more flexible above the water line, probably because of greater plasticizer retention. As in **Table 1**, the water extraction data showed a gain in water during the test. In summary, the data in **Table 2** indicate there is greater plasticizer retention in a non-aquatic environment, which results in a greater retention of flexibility even after nearly 30 years. This suggests that a PVC geomembrane in a non-aquatic environment, such as a landfill cover system, should experience similar or greater plasticizer retention than the below-water-level material, and similar or greater long-term performance.

| Test | Orientation | NSF-54 | PGI-1197 | UIUC | Test Method |
|---|---|---|---|---|---|
| Tensile Properties (Break Strength, lbs/in.) | MD<br>TD | 46<br>46 | 48<br>48 | 60<br>57 | ASTM D-882, Method A |
| Tensile Properties (Elongation at Break, %) | MD<br>TD | 325<br>325 | 350<br>350 | 369<br>351 | ASTM D-882, Method A |
| Tensile Properties (Secant Modulus at 100%) Strain, lbs/in.) | MD<br>TD | 20<br>20 | 23<br>23 | 48<br>47 | ASTM D-882, Method A |
| Tear Resistance (lbs.) (tensile strength with a notched specimen) | MD<br>TD | 6<br>6 | 6.5<br>6.5 | 11.3<br>10.6 | ASTM D-1004 |
| Seam Properties (Bonded Shear Strength, lbs/in.) | | 36.8 | 38.4 | 49.0 | ASTM D-882 |
| Hydrostatic Resistance (psi) | | 60 | 68 | 150 | ASTM D-751 (A) |
| Thickness (minimum, mils) | | 19 | 19 | 19 | ASTM D-5199,<br>ASTM D-1593 |
| Dimensional Stability (% change) | MD<br>TD | ±5<br>±5 | ±5<br>±5 | -4<br>-4 | ASTM D-1790 (100C, 0.25 hr) |
| Water Extraction (% change) | | -0.25 | -0.15 | 0.1 | ASTM D-3080 |
| Volatile Loss (% loss) | | 0.9 | 0.9 | 0.1 | ASTM D-1203 |
| Low Temperature Brittleness (% passing at -26C (-14.8F)) | | 80 | 80 | 89 | ASTM D-1790 |

***Table 2**: Test results for material exhumed from above water level and desiccated in accordance with corresponding ASTM test method.*

## Summary

After more than 29 years of service in an aquatic environment, this 20-mil PVC geomembrane retained its flexibility and strength, enabling it to perform as a successful water barrier. This indicates that plasticizer retention in an aquatic environment is not a problem even with 20-mil-thick material. These results are significant because they support the use of PVC geomembranes in non-aquatic applications. This is reinforced by comparison of the test results for material from above and below the water line that show greater plasticizer retention for above-water-line material. This case history also shows that PVC geomembrane material and its seams were not compromised or deteriorated by root penetration or microorganisms, even though the material was only 20 mil thick.

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