Analysis of thirty year old PVC geomembrane in the aquacultural industry

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ABSTRACT:. In 1971, twenty circular aquaculture ponds were constructed for the W.K. Kellogg Biological Research Station in Hickory Corners, Michigan. The 30.5 m diameter research ponds were lined using a 0.51 mm thick fish grade PVC geomembrane. Over the years the ponds became congested with dense, persistent stands of cattails and other vegetation, which required the ponds to be cleared and relined in September 2000 to allow the initiation of new experiments. This provided a unique opportunity to exhume nearly thirty-year-old PVC geomembranes and evaluate their engineering properties. It is important to note that none of the ponds were leaking or exhibiting any problems during the thirty years of service. One of the important outcomes of this study is the absence of root penetration through the liner or microorganisms adversely affecting the PVC geomembranes even though the ponds were overgrown with vegetation and filled with microorganisms. All of the tree and cattail roots grew down to the PVC geomembrane and then grew horizontally along the top surface of the geomembrane without damaging the geomembrane. The lack of holes in the geomembrane also suggests that the geomembrane not only resisted root penetration but also resisted biological attack from microorganisms. This is significant because the experiments conducted in the ponds introduced many types of microorganisms inside and outside of the ponds. Laboratory tensile testing showed that the tensile behavior is well within current specifications for new 0.51 mm thick PVC geomembranes. Test results also indicate that performing laboratory tests at in-situ moisture conditions provides a better estimate of the field properties of the PVC geomembranes than desiccating the material prior to testing as is required by ASTM Standard Test Method.

1 INTRODUCTION

In 1971, twenty circular aquaculture ponds were constructed for the W.K. Kellog Biological Research Station at the Michigan State University Facility in Hickory Corners, Michigan under a grant from the National Science Foundation. Eighteen of the ponds were for experimental purposes and two were 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 systems. These conditions provided the opportunity to conduct a number of significant experiments on species interaction and habitat selection in fishes.

The 30.5 m diameter research ponds were lined using a 0.51 mm thick fish grade PVC geomembrane. A fish grade PVC geomembrane is specially formulated to promote aquatic life through the omission of biocides from the basic PVC geomembrane formulation that may leach out over time. 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 eight feet deep with side slopes of three horizontal to one vertical. After installation, each PVC geomembrane was covered with one foot (0.30 m) of sandy soil cover.

Over time the ponds became congested with dense, persistent stands of cattails and other vegetation. These conditions made many types of experiments impossible, and thus, to start new aquaculture experiments, nine of the ponds were cleared and relined in September 2000. This provided a unique opportunity to exhume approximately thirty-year-old PVC geomembranes and evaluate their engineering properties. It is important to note that none of the ponds were leaking or exhibiting any problems during the thirty years of service. The nine ponds were re-lined with 0.51 mm PVC fish grade geomembrane liner fabricated in circular panels. Each new 1028 m^2 panel was made of material supplied by Polyone, Incorporated of Burlington, New Jersey. The circular panels were fabricated by Environmental Protection, Incorporated. Woolf Excavating of Kalamazoo, MI installed the one-piece liners in ponds 4 through 8, 10, 16, 17, and 18.

On September 13, 2000, a representative from the University of Illinois at Urbana-Champaign (UIUC) removed samples of the nearly 30-year old PVC geomembrane from the ponds. The samples were exhumed from three locations: (1) the side slopes above the waterline, (2) the side slopes below the waterline and under the cattails, and (3) the bottom of the ponds. The samples were sealed in large plastic bags to minimize moisture loss prior to testing and driven to the UIUC. Some of the samples were then shipped to TRI/Environmental in Austin, Texas for comparison testing

2 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 current specification values. The flexibility of the thirty-year-old material also is illustrated in Figure 1 by photographs of a tensile specimen of the sideslope material from below the waterline before and during tensile testing. It can be seen that the specimen is undergoing substantial elongation during testing without rupture. Material removed from the bottom of the pond was softer to the hand than the material from above the water line, probably because of less desiccation. 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 using in-situ conditions, i.e., without desiccation as required by ASTM Standard Test Methods, to properly assess the in-situ engineering properties. Desiccated specimens can be used for new material, but it is not recommended for exhumed materal because the geomembrane has already become acclimated to the field conditions.

At the center of each pond an inlet/outlet structure was constructed. This structure consisted of a concrete slab, approximately 0.75 m × 0.75 m, with the top level with the liner subgrade. The liner was placed over the concrete, sealed with butyl mastic, and fastened to the concrete using 38 mm × 95 mm redwood batten strips and concrete nails. This structure and the batten performed well over the nearly thirty years as indicated by no discoloration of the soil under the PVC geomembrane and 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. The mastic was soft and flexible after nearly 30 years, which resulted in an effective seal around the nails used to fasten down the strips.

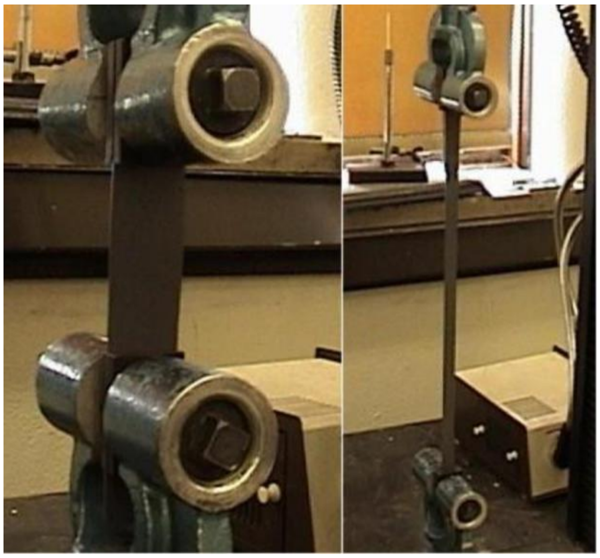

Figure 1. Exhumed PVC geomembrane before and during tensile testing.

3 ROOT PENETRATION AND MICROORGANISMS

One of the most important objectives of this study was to determine the effect, if any, of root penetration and microorganisms on the PVC geomembranes. The ponds were overgrown with vegetation, and had a large amount of cattails growing around the perimeter and in the middle of the ponds. 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 20 mm to 30 mm in diameter, with a mass of smaller roots around the main root. The root length was approximately 0.3 m to 1m. 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 0.51 mm thick geomembranes was found during field inspection or after holding the geomembrane over a light source in the laboratory.

In one of the ponds a small willow tree was growing about five feet down slope of the anchor trench but above the water level. The willow tree was approximately 4 m tall and had a trunk of 150 mm to 200 mm diameter. 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 1-1.5 m long, with some smaller roots extending up to 2 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 and 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 lack of observing holes in the field and in the laboratory in front of a light source also suggests that the geomembrane resisted biological attack from microorganisms. There was no surficial damage to the geomembrane to indicate microorganism attack, which is significant because the experiments introduced many types of microorganisms inside the ponds. This qualitative data suggests that there has been no detrimental effect on the geomembrane from root penetration or microorganisms in this harsh environment since 1971.

4 TESTS ON EXHUMED GEOMEMBRANE

Samples exhumed from above and below the waterline were tested at the UIUC to evaluate the effect of submergence and non-submergence on the engineering properties of the PVC geomembrane. Only samples exhumed from below the waterline 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 (1993), NSF-54, to quantify the changes in material and seam properties of the PVC geomembranes over the 29 years and 8 months of service. The NSF-54 specification was the applicable standard 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. The PGI-1197 specification, 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,which was last updated in 1993.

Some of the samples from each location were cleaned and allowed to acclimate and desiccate in the laboratory for 40 hours according to the applicable ASTM standard test methods. Other samples from each location were tested without allowing desiccation in the lab by storing the material in a moist room until testing. This non-desiccation procedure was implemented to provide a better estimate of the in-situ properties by keeping the geomembrane at the in-situ moisture content. The non-desiccated material provides a better simulation of the field moisture condition, and resulted in a more flexible material and better engineering properties. 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. The applicable ASTM testing specifications are listed in Table 1.

Table 1. Summary of tests and specifications

Test Description	ASTM Specification
Break strength	D 882, Method A
Elongation at break	D 882 (A)
Modulus at 100% strain	D 882 (A)
Tear resistance	D 1004
Bonded seam shear strength	D 882
Hydrostatic resistance	D 751 (A)
Thickness	D 5199, D 1593
Dimensional stability	D 1790 (100C, 0.25 hr)
Water extraction	D 3080
Volatile loss	D 1203
Low temperature brittleness	D 1790

The test results shown in Table 2 are for material that was obtained from near the bottom of one of the ponds and dessicated prior to testing. Review of Table 2 shows agreement between the test results obtained from the testing conducted at the UIUC and TRI/Environmental (TRI). More importantly, the results show that the thirty-year-old material properties exceed the NSF-54 required values and the more restrictive PGI-1197 values. For example, the tensile property data shows a sufficient percent elongation at break (greater than 350%) in both the MD and TD directions, which indicates that the material retained its flexibility. It can also be seen that the TRI/Environmental values of elongation at break are a little higher than the UIUC values but in agreement, and both exceed the NSF-54 and PGI-1197 values. 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/flexible material, while a high modulus indicates a stiffer material. The secant modulus is approximately two times higher than the specified values which indicates some hardening over the thirty years of service. However, some of this hardening may be caused by the desiccation of the material prior to testing. The hardening also may have contributed to the tensile break strength values comfortably exceeding both specifications. In summary, the engineering properties of the thirty-year-old submerged material exceeds both specifications even though the material was desiccated prior to testing.

Table 2. Dessicated, machine direction/transverse direction properties for dessicated material exhumed from below the water level

Test	NSF-54	PGI-1197	UIUC	TRI
Break strength (kN/m)	8.1	8.4	12.6/ 10.3	10.9/ 10.5
Elongation at break (%)	325	350	352/ 355	368/ 447
Modulus at 100% strain(kN/m)	3.5	4.0	9.8/8.9	*
Tear resistance (N)	26.7	28.9	59.2/ 53.8	37.4/ 36.4
Bonded seam shear strength (kN/m)	6.4	6.7	9.1	*
Hydrostatic resistance (kPa)	413	469	1029	710
Thickness (mm)	0.48	0.48	0.48	0.52
Dimensional stability (% change)	±5	±5	-4.7/ -1.4	-2.0/ 0.9
Water extraction (% change)	-0.25	-0.15	0.09	0.04
Volatile loss (% loss)	0.90	0.90	0.01	0.26
Low temperature brittleness (% passing)	80	80	83	100

*Not tested

The results of the water extraction and volatile loss tests also confirm sufficient plasticizer retention after thirty years. One interesting result from this testing is the water extraction data. The UIUC data indicates a gain in water during the test, as did the TRI/Environmental data 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 approximately thirty years was of particular interest. It can be seen from Table 2 that the bonded shear strength exceeds 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. In summary, factory solvent seams appear to be extremely durable, which is important because PVC geomembranes can have 100% factory seams. This facilitates installation and reduces installation costs. On large projects some field seaming may be required and research is being conducted to investigate the long-term durability of field PVC seams, but factory seams appear to be satisfactory.

Table 3. Machine direction/transverse direction properties for dessicated material exhumed from above the water level

Test	NSF-54	PGI-1197	UIUC
Break strength (kN/m)	8.1	8.4	10.5/10.0
Elongation at break (%)	325	350	369/351
Modulus at 100% strain(kN/m)	3.5	4.0	8.4/8.2
Tear resistance (N)	26.7	28.9	50.2/47.1
Bonded seam shear strength (kN/m)	6.4	6.7	8.6
Hydrostatic resistance (kPa)	413	469	1034
Thickness (mm)	0.48	0.48	0.48
Dimensional stability (% change)	±5	±5	-4.0/-4.0
Water extraction (% change)	-0.25	-0.15	0.10
Volatile loss (% loss)	0.90	0.90	0.10
Low temperature brittleness (% passing)	80	80	83

Plasticizer retention is more difficult in an aquatic environment than a non-aquatic environment because as the water or liquid continuously circulates, it provides a continuous opportunity for plasticizer migration versus a non-aquatic environment. In addition, the thinner the sheet, the larger the impact of surficial plasticizer loss on the engineering properties. For example, the percentage change in engineering properties can be greater for a 0.51 mm versus a 0.76 mm thick PVC geomembrane. Therefore, the test results on a 0.51 mm thick PVC geomembrane after nearly thirty years in an aquatic environment still exceeding the NSF-54 and PGI-1197 recommended values is significant. This indicates that the formulation was proper and the plasticizer was sufficiently retained even in an aquatic environment.

Material from above the waterline was also desiccated prior to testing in accordance with ASTM Standard Test Methods and the results are shown in Table 3. Above the waterline, i.e., a non-aquatic environment, it is anticipated that plasticizer retention would be higher than below the waterline, i.e. 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 2 and 3. For example, the break strength is lower for the material above the waterline indicating a slightly softer material than below the waterline. This additional plasticizer retention above the waterline is also reflected in the larger value of percent elongation at break (369% versus 352%) and lower a value of secant modulus (8.4 kN/m versus 9.8 kN/m) in the machine direction than the below waterline material. This suggests that the material is more flexible above the waterline probably because of greater plasticizer retention. As in Table 2, the water extraction data showed a gain in water during the test,which may be caused by desication prior to testing. In summary, the data in Table 3 shows there is greater plasticizer retention in a non-aquatic environment, which results in a greater retention of flexibility even after nearly thirty years. This suggests that a PVC geomembrane in non-aquatic environments, such as a landfill cover system, should experience excellent plasticizer retention and at a minimum better retention and performance than the below water level material, which exhibited good performance for nearly thirty years.

In addition to testing the dessicated material according to the applicable ASTM standards, specimens were maintained and tested at their in-situ water content. These results are summarized in Tables 4 and 5 for samples obtained below and above the water level, respectively. The secant modulus of the in-situ moisture content specimens is smaller than that of the dessicated material. This indicates that the PVC is more flexible at field moisture conditions than after it is dessicated. The elongation at break is also correspondingly larger for the non-dessicated material because it is more flexible than the desiccated material.

Table 4. Machine direction/transverse direction properties for non-dessicated material exhumed from below the water level

Test	NSF-54	PGI-1197	UIUC
Break strength (kN/m)	8.1	8.4	12.4/11.6
Elongation at break (%)	325	350	384/386
Modulus at 100% strain(kN/m)	3.5	4.0	9.4/9.1
Tear resistance (N)	26.7	28.9	57.8/50.3
Bonded seam shear strength (kN/m)	6.4	6.7	9.3
Hydrostatic resistance (kPa)	413	469	941
Thickness (mm)	0.48	0.48	.48
Dimensional stability (% change)	±5	±5	-2.5/-0.7
Water extraction (% change)	-0.25	-0.15	0.40
Volatile loss (% loss)	0.90	0.90	-1.13
Low temperature brittle-ness (% passing)	80	80	83

Table 5. In-situ, machine direction/transverse direction properties for non-desiccated material exhumed from above the water level

Test	NSF-54	PGI-1197	UIUC
Break strength (kN/m)	8.1	8.4	11.8/10.3
Elongation at break (%)	325	350	394/412
Modulus at 100% strain(kN/m)	3.5	4.0	8.4/7.9
Tear resistance (N)	26.7	28.9	49.8/46.7
Bonded seam shear strength (kN/m)	6.4	6.7	8.6
Hydrostatic resistance (kPa)	413	469	903
Thickness (mm)	0.48	0.48	0.48
Dimensional stability (% change)	±5	±5	-5.5/-5.7
Water extraction (% change)	-0.25	-0.15	-5.7
Volatile loss (% loss)	0.90	0.90	-0.11
Low temperature brittle-ness (% passing)	80	80	83

The in-situ results for the volatile loss and water extraction tests may be inaccurate because the ASTM procedure involves weighing samples before and after the tests and the specification was intended to be used for dessicated material. Therefore, the specification values are based on dessicated weights of the material may not be meaningful for material that was tested at this field water content. It is proposed herein that testing exhumed geomembrane at the in-situ conditions provides a better representation of the field behavior than desiccating the samples, Therefore, ASTM D3080 and D1203 should be modified to allow testing of exhumed geomembranes at field conditions.

5 CONCLUSION

After nearly thirty years of service in an aquatic environment, this 0.51 mm thick 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 0.51 mm thick material. These results are significant not only because they support the use of PVC geomembranes in aquatic applications but also support their use in non-aquatic applications, because a non-aquatic environment is less problematic in terms of plasticizer retention. This is reinforced by comparison of the test results for material from above and below the waterline that shows plasticizer retention is greater the above waterline material in Tables 2 and 3. This case history also shows that PVC geomembrane material and its seams are not compromised or deteriorated by root penetration or microorganisms after nearly thirty years, even though the material was only 0.51 mm thick.

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