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Performance Evaluation of A 23-Year Old Exposed HDPE Pond Liner

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ABSTRACT

Untreated water at an industrial site is pumped into a lined pond, held, and further conveyed to a water treatment plant. The pond has been in service for about 23 years. A study was undertaken to assess the condition of the pond liner and to evaluate its remaining serviceability. Exposed and unexposed samples of the primary geomembrane liner were obtained. Laboratory tests were performed to measure index properties (thickness, density, and carbon black content), mechanical properties (tensile properties, and stress crack resistance), and endurance properties (high pressure oxidative induction time). The test results for the exposed and unexposed were compared with one another and both were conservatively compared to the Geosynthetic Research Institute (GRI) test method GM13 specification values. Further, chemical resistance of the liner to the untreated water and sediment within the pond was evaluated using site-specific data. This paper presents an assessment of the 23-year old pond liner based on laboratory test results, site-specific data, as well as a literature review.

INTRODUCTION

A lined pond at an industrial site near Ducktown, Tennessee holds untreated water from site drainage, and further conveys to a water treatment plant. The pond is designed to hold about 7.6 million liters of water and is double-lined with a leak detection system (LDS). The liner system for the pond consists of (from top to bottom): (i) High Density Polyethylene (HDPE) 1.50 mm smooth geomembrane (GM) primary liner; (ii) HDPE geonet with top side as a 136 g/m^2 geotextile i.e., the leak detection layer; (iii) HDPE 1.00 mm smooth GM secondary liner; and (iv) 272 g/m^2 geotextile. The liner is anchored in a 0.3 m x 0.3 m anchor trench at 0.61 m offset from the crest of the pond. The primary function of the pond liner is untreated water containment.

The pond has been in service for about 23 years and has required minor repairs from time to time. Deposition of sediment in the pond calls for sediment removal and clean-up to maintain capacity and smooth operations. A study was undertaken to assess the current condition of the pond liner and to evaluate its remaining serviceability. Samples of the primary liner were obtained, and laboratory testing was performed. Subsequent sections discuss (i) the sampling and tests selection; (ii) results of the testing and evaluation criteria; (iii) liner evaluation utilizing test data and literature review; and (iv) conclusions and recommendations. The conclusions of the study were used to inform decisions relative to liner salvageability/replacement and selection of sediment removal alternative.

SAMPLING AND TESTS SELECTION

Two samples of the primary liner were obtained – one exposed from the crest of the pond and one unexposed from the anchor trench of the pond. The exposed sample was selected as being representative of the exposure of the liner to the atmosphere and effects of ultraviolet (UV) radiation. The unexposed sample was selected as being representative of the buried condition of the liner. Laboratory tests were performed to measure index properties: thickness (ASTM D 5199), density (ASTM D 1505), and carbon black content (CBC) (ASTM D 4218); mechanical properties: tensile properties (ASTM D 6693), and stress crack resistance (ASTM D 5397, App); and endurance properties: high pressure oxidative induction time (HP-OIT) (ASTM D 5885). All tests were performed in accordance with the applicable ASTM test standards.

Thickness and density were selected as index tests to verify the properties for the liner as-installed and to evaluate the properties in current conditions. Carbon black acts as a UV screening agent by absorbing UV light. CBC test was performed to evaluate the % carbon black remaining in the liner. Performance tests including the tensile properties, the HP-OIT, and stress crack resistance were selected to evaluate the tensile and endurance properties of the liner.

TEST RESULTS AND EVALUATION CRITERIA

The test results for the pond liner (1.50 mm smooth HDPE GM) were compared to one another (exposed and unexposed) and both were compared to the Geosynthetic Research Institute (GRI) test method GM13 titled "Test Methods, Test Properties and Testing Frequency for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes" (GRI-GM13, 2016). GRI-GM13 specification sets forth a set of minimum physical, mechanical, and chemical properties that are to be met or exceeded to ensure quality performance of HDPE GMs. In evaluating GM performance over time, it would be typical to compare test results to project design specifications. In absence of the project design specifications, however, a comparison with GRI-GM13 was considered warranted. The specification represents manufacturing quality control (MQC) and the values set forth are relative to a new GM product. The comparison of the pond liner test results with GRI-GM13 specification is, therefore, considered conservative.

Table 1 summarizes the test results and includes the GRI-GM13 specification values for a smooth HDPE GM for the corresponding test methods.

LINER EVALUATION: CURRENT CONDITION AND LIFETIME PREDICTION

This section presents an assessment of the liner based on the test results of physical, mechanical (tensile, stress crack), and endurance properties, as well as a literature review.

Physical Properties

Based on the index test results shown in Table 1, the liner was confirmed to have retained a thickness of at least 1.50 mm and a density of more than 0.940 g/cc characteristic of a HDPE product.

Table 1. Summary of GM Liner Testing for Pond

1.50 mm Smooth High Density Polyethylene (HDPE) Geomembrane				
	ASTM Test Method	**GRI-GM13 Specification**	Exposed Sample	Unexposed Sample
Thickness (mm)	D 5199	**1.50**	1.54	1.56
o Lowest individual of 10 values		**-10%**	1.50	1.52
Formulated Density (g/cc)	D 1505	**0.940**	0.951	0.947
Tensile Properties	D 6693			
o Yield Strength MD (kN/m)		**22**	29	28
o Yield Strength TD (kN/m)		**22**	31	28
o Break Strength MD (kN/m)		**40**	43	46
o Break Strength TD (kN/m)		**40**	45	45
o Yield Elongation MD (%)		**12**	21	19
o Yield Elongation TD (%)		**12**	19	17
o Break Elongation MD (%)		**700**	691	726
o Break Elongation TD (%)		**700**	720	734
Stress Crack Resistance (hr)	D 5397 (App)	**500**	>500	>500
Carbon Black Content (% range)	D 4218	**2.0 - 3.0**	2.61	2.63
High Pressure Oxidative Induction Time (HP OIT) (min)	D 5885	**400**	183	560

Tensile Properties

Quantitative data for tensile properties of GM are focused around the yield strength, the corresponding yield strain (referred to as elongation), the break strength, and break elongation. The results of the pond liner tensile properties indicate a characteristic HDPE GM response with a pronounced yield point, at a strain ranging from 17 to 21% (i.e., yield elongation), dropping slightly, and then extending in strain to approximately 700%. The yield strength of the liner ranges from 28 to 31 kN/m and exceeds the GRI-GM13 specification value of 22 kN/m, as shown in Table 1. In evaluating the sufficiency of the runout length and anchor trench design of the pond, the yield strength is a significant parameter. An allowable stress equal to a factored yield strength of the GM liner is typically used as a design input for anchor trench design. Calculations performed using a factored value of the measured yield strength indicate that the as-built runout length and anchor trench design/configuration was satisfactory. Relative to GRI-GM13, the measured yield strength of the exposed and the unexposed liner from the anchor trench far exceeds the minimum specified yield strength for a new GM. Overall, the liner is deemed to be performing satisfactorily from the standpoint of tensile properties.

Stress Crack Resistance

Stress crack resistance of semi-crystalline polymers such as HDPE has been widely studied and is identified as primarily being an intrinsic polymer property. Stress cracking is, therefore, largely a resin-dependent mechanism. A single point – notched constant tensile load (SP-NCTL) test is typically used to evaluate the stress crack resistance.

In absence of extensive laboratory testing and an established control curve (i.e., a full NCTL response curve for a resin formulation) for determination of transition time (defined as the time from ductile failure response to brittle failure response), the industry uses a conservative higher bound value for MQC purposes. The current recommendation for a minimum value for the transition time for an acceptable HDPE GM is 250 hours (GRI-GM10, 2015). A specimen that does not fail within 500 hours at a specific value of stress during the SP-NCTL test (usually selected as 30 percent of the yield stress), indicates the transition time for the GM is more than 250 hours and the result is considered satisfactory.

For the pond liner, both the exposed and unexposed liner sample specimens (five replicates each) were tested for stress crack resistance using the SP-NCTL test. The selected stress values were 30% of the yield stress as measured from ASTM D 6693. The number of hours to failure for all five replicates for both the exposed and unexposed sample specimens exceeded 500 hours, as shown in Table 1. This indicates that the transition time for the pond liner exceeds 250 hours. At 23 years of service, the liner exhibits satisfactory stress crack resistance and exceeds the values specified in GRI-GM13 and GRI-GM10 for a new GM liner.

Carbon Black Content

Carbon black acts as a UV screening agent by absorbing UV light and performs a radical trapping function by binding up damaging free radicals. For HDPE GMs, the recommended CBC is 2 to 3% (GRI-GM13). CBC of the exposed sample was measured to be 2.61% and that of the unexposed sample was measured to be 2.63%, as shown in Table 1. As anticipated, the CBC of the exposed sample was slightly lower than that of the unexposed sample. The depletion of carbon black in the exposed sample can be attributed to the liner exposure. Both measured values were within the recommended range and therefore, satisfactory.

Endurance Properties

Any phenomenon that causes polymeric chain scission, bond breaking, additive depletion, or extraction within the GM must be considered as degrading its long-term performance (Koerner, 2012). Degradation results in a GM becoming brittle in its stress-strain behavior over time. Long-term degradation of the liner was considered relative to the following causes: (i) exposure to UV light; (ii) chemical reaction with untreated water and sediments; and (iii) oxidation.

It is noted that the pond bottom liner and lower portion of pond side slopes are sediment laden and hence subject to potential chemical degradation from the sediment and untreated water. The liner on the upper portion of pond side slopes and pond crest runout is exposed, and hence subject to UV light and the atmosphere. The liner portion that is embedded in the anchor trench is covered and hence not subject to the causes of degradation mentioned above. Therefore, (in addition to GRI-GM13 specification values) the test results for the oxidation of the unexposed sample from the anchor trench was utilized as a baseline/threshold for the exposed liner test results. The liner resistance to chemical degradation and UV light exposure was assessed based on literature.

Chemical Resistance

In assessing chemical resistance, site-specific chemical characteristics were utilized. Maximum recorded concentrations for water discharge conveyed to the pond represented in the Record of Decision (ROD) (USEPA, 2012) for the site were used. Table 2 indicates maximum concentrations within the upper, middle, and lower sections (i.e., upstream sections of discharge) of the pond. Due to conditions during sampling, the analytical results for the lower section were not considered representative and maximum concentrations in the middle section were conservatively selected to be representative of the untreated water within the pond. Analytical results indicate high concentration of numerous dissolved metals, total sulfate, and total acidity. The analytical results also indicate a very low pH (min. 2.48).

Table 2. Maximum Concentrations for Discharge Conveyed to the Pond (adapted from USEPA, 2012)

		Discharge in OU3			Surface Water Inflows to OU3			
		Upper Section	Middle Section	Lower Section	Gypsum Pond Tributary	French Drain	NPC Diversion Tunnel	West Drainage Channel
Aluminum (diss)	µg/L	54,400	9,310	2,050	1,280	18,000	70,000	15,300
Antimony (diss)	µg/L	0.42 U	0.084 U	0.13	0.084 U	2 U	63 UJ	0.47 U
Arsenic (diss)	µg/L	11.3 J	3.6 J	0.22	1.1	85 J	73 J	3.4
Cadmium (diss)	µg/L	38.7	13.3 J	2.1	10.3	130	41 J	14.9 J
Chromium (diss)	µg/L	18.2 U	2.5	2.3	1.8 U	69.9	1.5 U	2.5
Cobalt (diss)	µg/L	2,000 J	1,730	94.5	274	21,200	4,900	551
Copper (diss)	µg/L	1,040	437	366	4.2	4,510	1,700	2,000
Iron (diss)	µg/L	2,120,000 J	438,000	13,100 J	172	3,760,000 J	330,000	2,210
Lead (diss)	µg/L	11.1	9.5	0.46	0.82	59.8	34	9.1
Manganese (diss)	µg/L	80,700	43,700	3,390	14,800	390,000	110,000	13,700
Mercury (diss)	µg/L	0.48 U	0.048 U	0.42 J	0.048 U	0.20 U	0.20 U	0.055 U
Nickel (diss)	µg/L	302	127	19	39.6	1,300	420 J	64.2
Selenium (diss)	µg/L	175 J	42.6 J	1.6	17.4	17 J	6.6	22.7 J
Zinc (diss)	µg/L	15,800 J	70,800	2,550	1,770	1,150,000 J	110,000	6,160
Sulfate (total)	mg/L	6,510 J	2,120	153	774	15,500	2,600	374
Acidity (total)	mg/L	4,070 J	1,300	268	20.6	8,000	1,580	114
pH	units	2.26 *	2.48 *	4.05 *	5.01 *	3.42 *	2.42 *	3.83 *

1 At the time of sampling, creek water was removed for treatment above Dam No. 3 and the Belltown diversion discharged below Dam No. 3
* minimum value
U – nondetected, value shown is detection limit; J – value is an estimate
Data are from Tables 5.3.15, 5.5.18, 5.5.19, 5.5.22, 5.5.24, and 5.5.27 in BWSC (2012a).

Chemical Compatibility of HDPE GM

Chemical resistance of pond liner to degradation by the contained liquids and solids, high in dissolved metals, total sulfate and total acidity, was an important consideration in evaluating the condition of the liner.

Literature notes that polyethylene used for producing GMs is essentially chemically inert (Apse, 1989) and does not undergo a change in its molecular structure with organic chemicals such as solvents (USEPA, 1988). The reaction of HDPE with chemicals has been extensively studied (Koerner et al., 1990; Rowe et al., 2009; Rowe et al., 2010a,b). In accelerated chemical compatibility testing of GMs conducted in the laboratory and in field investigations of GMs that have been installed as long as several decades, polyethylene GMs have been found to have good resistance to a wide variety of chemicals, including aliphatic and aromatic hydrocarbons, chlorinated and oxygenated solvents, crude petroleum solvents, alcohols, organic and inorganic acids, heavy metals, and salts (Matrecon, Inc., 1988; Hsuan et al., 1991; Brady et al., 1994; Eith and Koerner, 1998; Koerner and Hsuan, 2002; Sangam and Rowe, 2002; Koerner, 2012; Rowe et al., 2010b). Based on literature reported robust performance of HDPE relative to chemical exposure, the pond liner is expected to perform satisfactorily in relation to chemical degradation.

UV Light

To evaluate the degradation caused by UV light, laboratory weatherometer predictions are generally used. The weatherometers consist of accelerated simulation of direct UV light, high temperature, and moisture. Samples are subject to UV exposure at elevated temperatures, and mechanical properties (e.g., percent elongation retained) are measured at set intervals of light hours exposure. A 50% reduction in the value is taken as being the "half life." This value is customarily used by the polymer industry as being the materials lifetime prediction value (Koerner et al., 2011).

By comparing archived sample degradation times in the laboratory weatherometer to the actual lifetime of samples that failed in the field, Koerner (2012) has reported the following correlation:

1200 light hours in ASTM D7238 UV fluorescent exposure at 70 degrees Celsius	≅	One year in a hot and dry climate

Using this correlation, Koerner has reported the predicted lifetime of a HDPE GM in a dry and arid climate to be greater than 45 years. The climate at the pond site is much less intense and can be classified as humid subtropical climate characterized by hot humid summers, and mild to cool winters. The average annual high and low temperatures are 21°C and 6.7°C, respectively. The average annual rainfall is 1,527 mm (NOAA, 2018).

UV exposure testing was not performed for the pond liner. However, based on literature review for UV exposure of HDPE GMs, site climatology, and the satisfactory tests results for the CBC noted above, the HDPE liner of the pond is anticipated to perform satisfactorily relative to UV degradation for several years, if not decades, to come.

Oxidation

Oxidation of HDPE GM liners is caused by exposure to oxygen either through the atmosphere or through interaction with specific chemicals. Evaluation of antioxidants depletion in the tested samples is discussed first, below followed by a discussion of the potential for oxidative degradation of the pond liner due to exposure to acidic environment and transition metals.

Evaluation of Antioxidants Depletion

Antioxidants are added to prevent polymer degradation during processing and to extend GM service life by delaying degradation caused by oxidation reactions (Hsuan and Koerner, 1998). HDPE GM formulations generally consist of approximately 0.5% to 1% antioxidants. Once the antioxidants are depleted, additional oxygen diffusion into the GM and scission of polymer chains begins. Literature reports three distinct lifetime stages in aging of GMs as shown on Figure 1. Stage A represents the time required for depletion of antioxidants. Stage B represents the induction time defined as time between full depletion of antioxidants and onset of measurable degradation of engineering properties. Stage C represents the time for a selected property to reach its half-life (e.g., 50% reduction in elongation at failure).

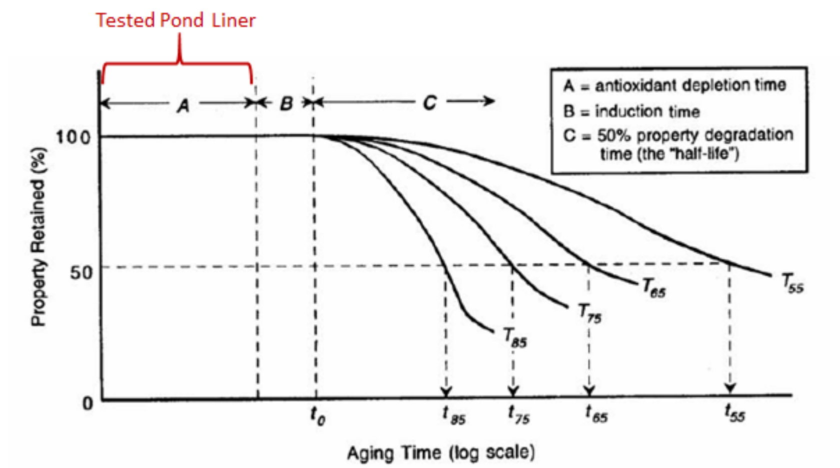

Figure 1. Three Individual Stages in Aging of GMs (Koerner et al., 2011)

The depletion of antioxidants for the pond liner was assessed by performing HP-OIT tests on the exposed and unexposed samples. The OIT was measured to be 183 minutes and 560 minutes, respectively, as shown in Table 1. The GRI-GM13 specifies OIT for new GMs to be greater than 400 minutes. In this light, the measured OIT for the unexposed liner is very encouraging and provides a baseline for comparison with the exposed liner. It is intuitive that antioxidants depletion was measured in the exposed GM. The OIT of 183 minutes indicates depletion from about 560 minutes (considering the unexposed as baseline) over the service life of 23 years, which indicates the exposed liner is still within Stage A of GM aging as shown on Figure 1.

Oxidative Degradation by Acidic Environment

HDPE is relatively inert in both acidic and basic environments. Rowe and Abdelaal (2016) examined the effects of very low pH on HDPE GM antioxidants depletion by immersing GM specimens in seven different low pH (0.5, 1.25, and 2.0) solutions with variations in metal concentrations and surfactants at temperatures of 40, 65, 75, 85, and 95°C over a period of 3 years. The results show minimal antioxidant depletion with depletion rates ranging from 0.0038/month to 1.63/month and the residual HP-OIT values ranging from 268 to more than 825.

Although HDPE is relatively inert in acidic environments, action of oxidizing acids at high concentrations (e.g., sulfuric acid at a concentration greater than 70% (pH of 0.3)) (Brydson, 1999; Scheirs, 2009) may lead to excessive degradation. The pH of untreated water in the pond is on the order of 2.5 (i.e., very acidic). Over the past approximately 23 years, the pond bottom liner has likely been continually exposed to highly acidic untreated water and potentially to sulfuric acid. Considering the oxidation potential at high acidic concentrations, excessive degradation of the pond bottom liner is likely. Since tests performed on samples exhumed from the crest and anchor trench may not accurately represent the pond bottom liner conditions, further evaluations (e.g., testing pond bottom liner for OIT) are being considered.

Oxidative Degradation by Transition Metals

Transition metals can catalyze abiotic oxidation of polyethylene, resulting in a product that is more susceptible to biodegradation (Corti et al., 2010; Roy et al., 2011; Zheng et al., 2005). In immersion testing of HDPE GM with different leachates, including some that included transition metals in a trace metal solution with a total concentration more than 3,000 mg/l, Rowe et al. (2008) found the presence of transition metals to have little or no effect on the antioxidant depletion rate.

Several transition metals including Chromium, Manganese, Iron, Cobalt, Nickel, Copper, Zinc, Cadmium, and Mercury were reported in the discharge water samples. The concentrations of Iron, Manganese and Zinc, were the highest and were reported to be 438 mg/l, 43.7 mg/l, and 70.8 mg/l, respectively. The total concentration of transition metals in the middle section of the contributing discharge was calculated to be 555 mg/l. Based on this total concentration, chemical degradation of the pond liner due to transition metals is not anticipated.

Summary of Oxidation Evaluation

The results of the HP-OIT testing were encouraging and indicate that antioxidants are still present. The liner is in Stage A of GM aging, and has several years, if not decades, of remaining serviceable life in so far as oxidation of the exposed or buried liner is concerned. The continued likely exposure of the pond bottom and side slope liner to extreme acidic environments for more than two decades suggest that oxidative degradation may exist. Further evaluations such as chemical resistance testing and OIT testing of the pond bottom liner are being considered.

FIELD OBSERVATIONS

Several site visits were made to visually assess the condition of the pond liner over the past year. The exposed HDPE primary GM liner does not appear to show obvious distresses (such as tears, cracks, or excessive discoloration). The liner welds also did not appear to show obvious distresses. A thin layer of oxidation precipitate coat appears to have been formed on the bottom and side slopes. The anchor trench of the pond was observed to be functioning properly all along the perimeter with minimal wrinkles and minimal areas of tension. Based on filed observations including those made during pond water drawdown, obvious distresses were not seen in the exposed pond liner that would be attributed to the discussed degradation mechanisms. Further, the LDS of the pond is actively monitored. Leaks have not been detected for the past several years, except for one instance in 2017 wherein GM patching was performed at two locations to stop the leaks. The lack of leaks observed in the LDS further confirms the performance of the pond primary liner and validates the positive laboratory test results obtained.

CONCLUSIONS AND RECOMMENDATIONS

Based on the laboratory testing performed, analyses of the results, and evaluation of the liner presented herein compounded with observations made in the field, it is concluded that the pond primary liner is performing satisfactorily. From the standpoint of endurance properties (i.e., UV degradation, chemical resistance, and oxidative degradation), the testing and evaluation indicate that the liner will stay serviceable for several years, if not decades. Observations made in the field including monitoring of the LDS validate the encouraging laboratory results. Therefore, the liner was concluded to be salvageable, so far as sediment removal options were concerned.

Attention was called to potential oxidative degradation at specific locations of the liner and further testing and evaluations were recommended. Further, pond liner testing was recommended to be performed every 3 to 5 years to re-evaluate and confirm the conclusions reached herein.

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