A LITERATURE REVIEW ON LIFETIME PREDICTION OF THIN HDPE GEOMEMBRANES IN THE EXPOSED ENVIRONMENT

R. Denis[1], D. Tan[2], and D. Cao[3]
[1]Solmax International Inc.; Tel: +1-450 929 1234; Fax: +1-450 929 2547; Email: rdenis@solmax.com
[2]Solmax International Asia Pacific; Tel: +603 3375 3600; Fax: +603 3101 2689; Email: dtan@solmax.com
[3]Solmax International Inc.; Tel: +1-450 929 1234; Fax: +1-450 929 2547; Email: dcao@solmax.com

ABSTRACT

Use of thin (≤ 0.75mm) high-density polyethylene (HDPE) geomembranes for applications in the exposed environment such as salt evaporation ponds, landfill capping and aquaculture are common in South East Asia. Many have researched on the durability and lifetime prediction of HDPE geomembranes particularly for the landfill industry where the common usage thickness ranges between 1.0mm to 2.5mm depending on the regulation of respective countries around the world. There is however a paucity of industry information on the lifetime prediction of thin HDPE geomembranes used in the exposed environment. This paper seeks to collate available information on the durability and lifetime prediction of HDPE geomembranes for various thicknesses and proposes a way forward to manage the performance risk for project stakeholders where thin HDPE geomembranes in the exposed environment are used.

Keywords: Thin geomembrane, exposed, lifetime prediction, antioxidant depletion

INTRODUCTION

The Geosynthetic Research Institutes (GRI) specification no. GM13 is a standard for HDPE geomembranes (GMB) that is widely accepted worldwide, commonly referred to and adapted accordingly by various national standards as well as respective project specifications. GRI GM 13 covers HDPE GMBs of thicknesses ranging between 0.75mm to 3.00mm. From the authors, experience and observation throughout South East Asia, thinner gauge HDPE GMBs are commonly used such as 0.5mm for salt evaporation ponds, 0.5mm to 0.75mm for shrimp aquaculture ponds and 0.75mm for landfill capping just to name a few amongst other applications. These thinner gauge HDPE GMBs are commonly manufactured to specification values that are extrapolated (apart from 0.75mm) from GRI GM13 as they are not explicitly covered by the standard.

The applications that use thinner gauge HDPE GMBs are commonly constructed in the exposed environment such as landfill capping or partially exposed environment such as from the pond or canal water freeboard level to the anchor trench at the crest of the bund. It has been widely published and universally accepted that GMBs constructed in the exposed environment has a shorter lifespan compared to the buried or covered environment due to adverse degradation mechanisms such as rich natural presence of oxygen, UV degradation from photo-oxidation and increase temperature degradation due to thermo-oxidation (Rowe et al. 2002; Koerner et al. 2012).

Additives in the form of carbon black and antioxidants are generally used to retard and inhibit the photo-oxidation (UV) and thermo-oxidation (temperature) degradation mechanism of GMBs. Given the understanding that antioxidant additives may be extracted from the GMB through surface leaching or evaporate in the case of volatile additives or migration of additives from the core of the GMB to its material surface through diffusion (Kay et al. 2004), it has been theorized that a thinner gauge HDPE GMB would have lesser durability resistance when compared to thicker HDPE GMBs. Thickness effect on the ageing of HDPE GMBs has only been studied by a few (Rowe et. al. 2010) and remains a research needs especially for UV exposed GMBs (Koerner et al. 2012).

As such, the durability of thinner gauge HDPE GMBs coupled with installation in the exposed environment posed a significant challenge to the project stakeholders (manufacturers, consultants as well as project owners) where HDPE GMB lifetime prediction is in question. The service life of HDPE GMB is generally accepted and arbitrarily defined by the period until it reaches its „half-life i.e. 50% reduction of a specific design property such as tensile strength (Hsuan and Koerner 1995). Another commonly adopted definition for service life of HDPE GMB is the duration where the GMB is able to perform effectively as a contaminant hydraulic and diffusive barrier (Rowe et al. 2010). Regardless of the definition, it should be noted that the HDPE GMB does not disintegrate at an instance but still exist and able to function as per intended purpose but at a reduced performance level below original design assumptions.

In order to manage the extent of the subject matter, discussions in this paper covers only HDPE GMBs that are manufactured to specifications that are similar to GRI GM 13 standard and does not include other GMBs such as linear low-density polyethylenes (LLDPEs), scrim reinforced polyethylene, polyvinyl chlorides (PVCs) etc.

Testing results discussed in this paper mainly focuses on the oxidation induction time (OIT) values as this is the main durability parameter used for Stage A lifetime prediction of HDPE GMBs. In summary, Stage A measures the period where antioxidants are fully depleted until a state where it no longer offers protection to the GMB from degradation mechanisms such as photo-oxidation and thermo-oxidation. Stage B is the induction time starting from full depletion of antioxidants to onset of polymer degradation and Stage C is the time it takes to reach 50% of a specific HDPE GMB design property. The lifetime of a HDPE GMB is then the sum of periods A, B and C (Hsuan and Koerner 1998).

High pressure oxidative induction time (HPOIT) tests were also sometimes carried out in place or on top of the standard (Std) OIT test. The testing method for Std-OIT and HP-OIT are essentially the same except for testing condition variation such as the pressure and temperature maintained during oxidation. The various advantages and disadvantages between the Std-OIT and HP-OIT test have been discussed by Hsuan and Koerner (1998).

LABORATORY STUDIES

Hsuan and Koerner (1998) showed that antioxidant depletion can be extrapolated through the following expression:

$$\ln(\text{OIT}) = \ln(P) - (S)(t) \qquad (1)$$

where P = Initial (original) value of OIT of the GMB (in minutes); S = OIT depletion rate (in month^{-1}); t = incubation (ageing) time (in months); and OIT = OIT time (in minutes).

It should be noted that equation (1) is suitable to be used to estimate OIT depletion time for both the Std-OIT as well as the HP-OIT test methods.

Sangam and Rowe (2002) and Rowe et al. (2009) produced inferred antioxidant depletion rates following the first-order decay model used in extrapolation of antioxidant depletion illustrated in equation (1) to laboratory studies of 2.0mm HDPE GMBs that has been ageing for 8 – 10 years in conditions exposed to air, water and synthetic leachate at temperatures 22^{0}C, 40^{0}C, 55^{0}C, 70^{0}C, and 85^{0}C. Some of the samples have already reached Stage B and / or Stage C especially for samples incubated at 85^{0}C. This study is useful for lifetime prediction of HDPE GMBs in the buried environment beneath water or leachate as well as acts as a reference for HDPE GMB lifetime prediction in the exposed environment.

Islam and Rowe (2007) and Rowe et al. (2010) carried out study on the depletion of antioxidants for commercially available GRI GM 13 compliant HDPE GMB of thicknesses 1.5mm, 2.0mm and 2.5mm immersed in synthetic leachate at 22^{0}C, 55^{0}C, 70^{0}C, and 85^{0}C. The study showed that antioxidant depletion rates were faster in the thinner HDPE GMB compared to the thicker sheets. Further refinement on the study of HDPE GMB thickness sensitivity to antioxidant depletion rate was carried out by Ewais and Rowe (2012) using HDPE GMBs made from the same resin lot immersed in synthetic leachate under 26^{0}C, 40^{0}C, 55^{0}C, 70^{0}C, and 85^{0}C. Findings from the refined study indicated that (other things being equal) time to antioxidant depletion increased by 5% to 16% when the HDPE GMB thickness increased from 1.5mm to 2.0mm and 13% to 30% for thickness increase from 1.5mm to 2.4mm; the higher the temperature, the higher the increase in percentage.

Although the above studies on thickness sensitivities to antioxidant depletion rates are simulated for buried applications as photo-oxidation degradation mechanism was not part of the parameters simulated, the findings at least provided a reference for antioxidant depletion rate estimates in the exposed environment.

Martin (2005) showed that a 0.75mm polyolefin GMB requires additional antioxidant of 1000 to 2000 minutes of HPOIT to perform equally with a 1.5mm HDPE GMB that is without additional antioxidants stabilized with carbon black alone. The study was carried out for the exposed environment where a correlation of 1000 hours accelerated exposure equals to 1 year of natural exposure in Edmonton, Canada may be used for purposes of warranties. This study was benchmarked after Wagner and Ramsey (2003) who provided a loose correlation of 500 to 1500 hours of accelerated exposure equaling to 1 year of field exposure used by the paint and coatings industry (Martin 2005). Incidental conclusion from this study showed that a 1.5mm HDPE GMB stabilized only with carbon black without additional antioxidants was able to provide service life in excess of 20 years in the exposed environment of Edmonton, Canada.

Koerner et al. (2012) carried out laboratory studies on 6 GMB types including a 1.5mm HDPE GMB using ultraviolet fluorescent weatherometers following ASTM D7238 and calibrated it against 4 field failures of flexible polypropylene (fPP) GMBs located in West Texas and Southern California, USA. The correlation is approximately 1 year of service life in a hot climate similar to where the failure samples were obtained approximately equal to 1200 light hours of GMB exposure at 70^{0}C in an ASTM D7238 device. The correlation of laboratory incubated HDPE GMBs to field failure samples of fPP GMBs was justified by the authors as the two GMBs are polyolefins. The study also interestingly indicated a lifetime prediction for buried GMBs to be approximately 10 times the prediction for exposed lifetime. This study currently predicts a 1.5mm HDPE GMB manufactured to GRI GM 13 standard has an exposed lifetime prediction of approximately 50 years under the hot climate of West Texas and Southern California, USA.

Although data and findings from laboratory studies are vital, field performance are essential to validate the results from laboratory simulation.

FIELD PERFORMANCE

Adams and Wagner studied the performance of a 10 year old 1.0mm HDPE GMB that was used to line the lagoons for a fruit concentrate wastewater processing plant in Ohio, USA. Significant portions of the liner were exposed to UV radiation but majority of the liner was under the wastewater with typical pH levels of 5 to 8. Results from the testing of HDPE GMB on both the exposed and the unexposed samples concluded that there were no statistically significant changes to the physical properties of the HDPE GMB except for the increase in elongation at yield and a decrease in elongation at break. The results of OIT test was inconclusive as there were no significant difference between the exposed (43 minutes) compared to the unexposed (38 minutes). However, the presence of remaining OIT within the GMB after 10 years clearly showed that it has preserved the mechanical properties of the GMB over the years.

Tarnowski and Baldauf carried out studies on exposed HDPE GMBs with various thicknesses at 3 locations namely Galing in Germany (2.5mm), Sarchesmeh in Iran (2.5mm) and Levante in Spain (2.0mm). After 25 years of exposure to high annual irradiation energy of 190 kLy in Sarchesmeh, Iran, mechanical properties tests carried out on sample obtained above the water level showed no statistically significant change when compared to initial state. However, durability tests such as remaining OIT minutes as well as SP-NCTL were not carried out. Two samples were obtained from Levante, Spain 11 years after construction. The SP-NCTL and OIT tests results clearly showed that the durability performance of the exposed sample is lower than the sample obtained at intermittent water level. Extensive mechanical and durability tests were carried out for the 2.5mm thick HDPE GMBs in Galing, Germany. One interesting test method was done where OIT was carried out for the top 0.9mm of the 2.5mm thick HDPE GMB as well as at the middle layer of the HDPE GMB. For the 21 year old exposed sample where OIT test was carried out under 200^{0}C condition, remaining OIT of 5 minutes were obtained for the top layer and 65 minutes for the middle layer. This and amongst other tests led the authors to suggest that thickness plays a very significant role on antioxidant depletion and ultimately affecting the durability of the HDPE GMB liner.

Hsuan et al. (1991) investigated a 7 year old domestic solid waste leachate storage facility that was decommissioned and reconstructed. The reason for reconstruction was not because the liner had failed but it was to replace the surface impoundment with an underground storage tank system. It was reported that the liner had not “failed” in any manner. The tensile properties such as yield strength for the sheets and peel and shear strength for the seam remained the same. A total of 12 samples were exhumed from 3 separate GMB panels located at the west side of the surface impoundment. The samples were taken from 4 various locations i.e. a pond bottom, intermittent water level, above water level and in the anchor trench. It was observed that the OIT depleted the most for the exposed samples compared to the other 3 locations.

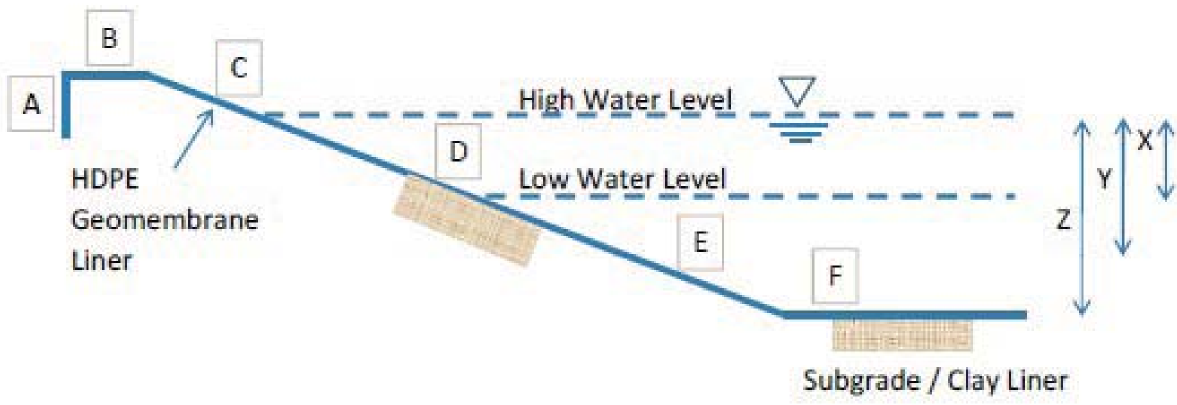
Swihart and Haynes (2002) from the US Bureau of Reclamation reported the performance of an exposed 2.0mm HDPE GMB as part of its long term study to investigate the most suitable canal lining system. The study comprised of evaluating the Benefit / Cost of various canal lining system by examining various factors such as installation cost, durability of the lining system under exposed conditions as well as convenience of maintenance and its recurring cost. Other lining systems that were evaluated as part of this study included fluid applied membrane, concrete lining as well as GMB with concrete cover. After 10 years, the exposed 2.0mm HDPE GMB were reported to be in excellent condition with only minor mechanical damage that was likely to be caused by testing and maintenance work along the canal. OIT measurements on the archived samples as well as the site exhumed samples were sent to the GRI for testing. Although the exposed section showed OIT loss of 16% higher than the buried section, the report concluded that the difference was not significant enough at time of testing to differentiate the benefits of buried and exposed section and recommended further long term testing.

Ivy (2002) investigated on the properties of 2.5mm HDPE GMBs after 20 years of service as pond liners for a 500MW steam electric generating station in Colorado, USA. 3 samples were obtained from the intermittent quality (IQ) ponds at locations above water level at east side, intermittent water level at east side and above water level at west side. The samples were obtained from a weld so that the GMB may be tested for properties at the portion that is exposed to UV as well as at the bottom overlap portion that is not exposed to UV. 2 further samples were obtained from evaporation ponds at locations above water level at south side and above water level at west side. Results from the standard OIT and high pressure OIT from all 5 locations showed no significant difference between the exposed and the non exposed portion. From these results, Ivy (2002) postulated that OIT values appear to be independent on whether the HDPE GMB was exposed or not.

Rowe et al. (2003) reported on a 14 year old 1.5mm HDPE GMB used to line a lagoon storing nonhazardous leachate from industrial, municipal and commercial landfill in Ontario, Canada. GMB samples were exhumed from the anchor trench, above leachate level, intermittent leachate level, below leachate level and at bottom of the lagoon. The lowest OIT was recorded at the exposed slope (1.8 minutes from average of 12 tests). Rowe et al. (2003) had envisaged this result from reasoning that the GMB located above leachate level was exposed to the greatest amount of oxygen coupled with highest intensity of photo-oxidation and thermo-oxidation.

Yako et al. (2010) evaluated an exposed 20-year old 2.0mm HDPE GMB used to line an ash surface impoundment for Brayton Point Power Plant in Somerset, Massachusetts, USA. 3 samples were obtained from location at the horizontal runout, exposed side slope and below waste level near toe of slope. Interestingly, test results showed that the exposed side slope had the lowest remaining OIT of 35 minutes compared to 63 minutes for the horizontal runout which is also exposed and 80 minutes for the buried section. The results of OIT is identical to the findings from another durability test (stress crack resistance) that was carried out which showed the resistance for the exposed slope is the lowest followed by the horizontal runout and lastly the buried section. However, it is clear from this evaluation that the buried section had undergone degradation to a lesser degree compared to the exposed sections.

OIT values obtained from field exhumed sample provides valuable data for lifetime prediction of HDPE GMBs in order to establish a reasonably accurate Stage A duration. Equation (1) may be used to compute the antioxidant depletion rate of exposed HDPE GMBs exhumed from the field if the original OIT (*P*) is known or may be logically estimated (Rowe et al. 2003). Figure 1 illustrates the location where samples were obtained as described by the respective authors and Table 1 summarizes the OIT values from all the reported field performance.



Note: A – Anchor Trench; B – Horizontal Runout; C – Above Water/Wastewater/Waste Level; D – Intermittent Level; E – Below Water/Wastewater/Waste Level; F – Bottom of Lagoon/Pond

Fig. 1 Schematic diagram illustrating location of field exhumed samples.

Table 1 Summary of OIT data from field performance.

(Reference) HDPE GM Thickness (mm)	Project Site	Sample Location	[Year of Construction] *t* (years)	*P* (min.)	OIT (min.)
(Adams and Wagner) 1.0mm	Ohio,	C	[1988]	-	43
	USA	E	10		38
(Tarnowski and Baldauf) 2.5mm			[1974]		
Top 0.9mm	Galing I,	C	21	-	7.1
Mid. 0.9mm	Germany				8.8
Top 0.9mm		C	31	-	0
Mid. 0.9mm					4
Top 0.9mm	Galing II,	C	[1984]	-	5
Mid. 0.9mm	Germany		21		65
2.0mm	Levante,	C	[1994]	145	56 - 67
	Spain	D	11		107 - 110
(Hsuan et al. 1991) 1.5mm		A	7	~ 50*2	27
		C			11
		D			25
		F			35
(Swihart and Haynes 2002)		C	[1992]	73	47
2.0mm		E	10		56
(Ivy 2002)*1 2.5mm	Colorado,	C (East)	[1980]	~ 50*2	49 (47)
	USA	D (East)	20		36 (39)
		C (West)			27 (27)
		C (South)			33 (33)
		C (West)			38 (37)
(Rowe et al. 2003) 1.5mm	Ontario,	A	[1982]	~ 50*2	3.5
	Canada	C	14		1.8
		D			3.3
		E			6.3
		F			5.0
(Yako et al. 2010) 2.0mm	Somerset,	B	[1989]	-	63
	Massachusetts,	C	20		35
	USA	E			80

Note: *1 Values of OIT(min.) in ( ) are taken from the seam bottom overlap; *2 Values of *P* (min.) are estimated based on typical values for HDPE GMBs manufactured during this period (Ivy 2002; Rowe et al. 2003).

DISCUSSIONS

Adams and Wagner and Ivy (2002) presented findings that imply the depletion of antioxidant is not dependent on the exposure or buried condition of HDPE GMBs. These findings are in stark contradiction with the observations from Hsuan et al. (1991), Rowe et al. (2003), Yako et al. (2010) and Koerner et al. (2012). Swihart and Haynes (2002) also reported lower OIT retention time for the exposed GMB albeit at lower differentiation compared to the buried section. As it is generally acknowledged that GMBs exposed to UV radiation would undergo greater degradation effects compared to the buried environment, further evaluation needs to be carried out on the exposure conditions of the site to observe whether the chemical degradation effects for the buried location outweighs or neutralizes the additional effects of photo-oxidation. It is also worth evaluating the temperature of the wastewater and see if it is higher than the thermo-oxidation effect arising due to UV radiation. The intensity of UV radiation at the said location should also be investigated. Furthermore, OIT was carried out on the full cross section of the 2.5mm thick HDPE GMB at Colorado, USA site. As the HDPE GMB is very thick, the authors postulate that should the OIT be carried out on the outer and middle layer, then significant differences in OIT values is likely to be observed similar to the findings of Tarnowski and Baldauf for the Galing, Germany site.

Islam and Rowe (2007), Rowe et al. (2010) and Ewais and Rowe (2012) showed from laboratory studies that time to antioxidant depletion increased with increasing HDPE GMB thickness. Although this laboratory study simulates buried conditions, the findings on the sensitivity of HDPE GMB thickness to antioxidant depletion agrees well with the field performance observation as reported by

Tarnowski and Baldauf for the Galing, Germany site.

Several correlations of accelerated laboratory exposure to field exposure have been proposed. (Martin 2005; Koerner et al. 2012). This correlation however is only applicable to similar weather conditions where the respective field samples were taken for calibration as well as only applicable to the respective HDPE GMB thickness used in the studies. Hence, such correlation may only be referred to as a guide. Further evaluation using UV radiation maps such as that illustrated in Figs. 2 or 3 may be used as necessary weather correction factors for evaluation of suitability and lifetime prediction of exposed HDPE GMBs for the new location under evaluation.

Given the paucity of information, the difficult part is the evaluation of different HDPE GMB thickness (especially thinner gauge HDPE GMBs) for lifetime prediction in the exposed environment and this is currently a research need.

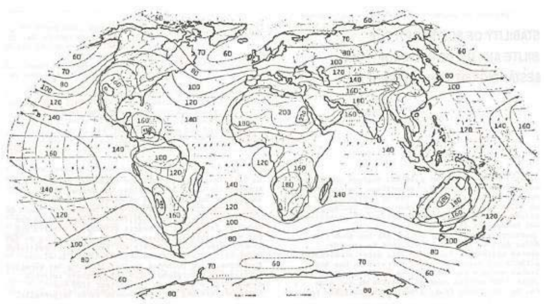


Fig. 2 Annual irradiation energy isocurves in "kLy" after Van Wilk and Stoezer (1986) (Koerner et al. 2012)

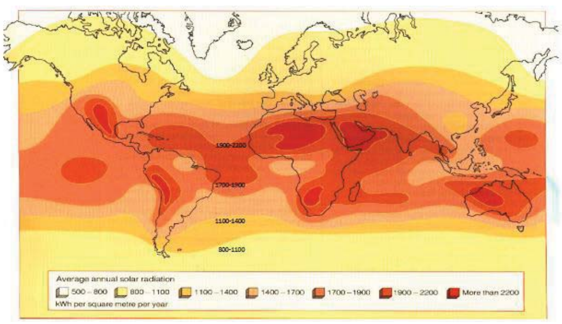


Fig. 3 Average annual solar Radiation in "kWh/m^2.year" (Keller et al. 2009)

CONCLUSIONS

Assessment of field exhumed HDPE GMB samples over its entire service life is the ideal method which is most representative of actual conditions. Although this approach is not suitable for thicker HDPE GMBs in both the buried and exposed environment as illustrated by the laboratory studies and field performance referenced above, it is however likely to be within the reasonable observational period for thinner gauge HDPE GMBs in the exposed environment. As such, this method is advocated for the medium term research needs. This however needs to be supplemented with laboratory studies for correlation to different HDPE GMB thicknesses.

Given the current available information, the authors propose to employ a careful extrapolation method that is partly based on engineering judgment to be used for assessment of lifetime prediction of thin HDPE GMBs in the exposed environment for the immediate needs of current projects before further information are made available from further research in the near future.

ACKNOWLEDGEMENTS

The authors are grateful to their colleagues Guy Elie and Simon Gilbert St-Pierre who provided valuable critique of the paper.

REFERENCES

Adams M.W. and Wagner N. Forensic Study of an HDPE Liner after 10 years of Exposure. Web reference: http://geosynthetica.net/tech_docs/10yearExAdamsWagner.pdf

ASTM D7238 - 06 Standard Test Method for Effect of Exposure of Unreinforced Polyolefin Geomembrane Using Fluorescent UV Condensation Apparatus.

Ewais A.R.M. and Rowe R.K. (2012). The Effect of thickness on OIT depletion of HDPE geomembranes made from the same resin and immersed in synthetic leachate. Proc. of the Second Pan American Geosynthetics Conference and Exhibition (GeoAmericas 2012), Lima, Perú.

GSI (2011). Test Methods, Test Properties and Testing Frequency for HDPE Smooth and Textured Geomembranes. GRI Test Method GM13 Rev. 10, Geosynthetic Institute, Folsom, PA, U.S.A.

Hsuan Y.G. and Koerner R.M. (1995). Long Term Durability of HDPE Geomembranes: Part I – Depletion of Antioxidants. GRI Report #16, Drexel University, Philadelphia, PA, U.S.A.

Hsuan Y.G., Lord Jr. A.E. and Koerner R.M. (1991). Effects of outdoor exposure on a High Density Polyethylene Geomembrane. Proc. of Geosynthetics '91 Conference, Atlanta, U.S.A.

Hsuan Y.G. and Koerner R.M. (1998). Antioxidant depletion lifetime in high density polyethylene geomembranes. Journal of Geotechnical andGeoenvironmental Engineering ASCE. 124(6): 532 – 541.

Islam M.Z. and Rowe R.K. (2007). Effect of HDPE geomembrane thickness on the depletion of antioxidants. Proc. of OttawaGeo 2007, Ottawa, Canada: 2129 – 2134.

Ivy N. (2002). HDPE Geomembrane after 20 years of Service. Geotechnical Fabrics Report, IFAI, Roseville, MN, June/July 2002: 18 – 20.

Kay D., Blond E. and Mlynarek J. (2004). Geosynthetic durability: A polymer chemistry issue. Proc. of Géo-Québec 2004: 57th Canadian Geotechnical Conference and 5th Joint CGS/IAH-CNC Conference, Québec, Canada, Session 4D: 1 – 14.

Keller J., Gernjak W. and Pratt S. (2009). Technology options for coal seam gas (CSG) water management. Proc. SPE Technical Seminar 7. Advanced Water Management Centre and University of Queensland, Queensland, Australia. (Presentation Only)

Koerner R.M., Koerner G.R. and Hsuan Y.G. (2012). Lifetime Prediction of Laboratory UV Exposed Geomembranes: Part I – Using a Correlation Factor. GRI Report #42, Geosynthetic Institute, Folsom, PA, U.S.A.

Martin D. (2005). UV resistance in thin film geomembranes accelerated and natural weathering studies. Proc. of Geo- Frontiers 2005, Geotechnical Special Publication 142 – Waste Containment and Remediation, Austin, Texas, U.S.A.

Rowe R.K. and Sangam H.P. (2002). Durability of HDPE geomembranes. Geotextiles and Geomembranes 20: 77 – 95.

Rowe R.K., Sangam H.P. and Lake C.B. (2003). Evaluation of an HDPE geomembrane after 14 years as a leachate lagoon liner. Canadian Geotechnical Journal 40: 536 – 550.

Rowe R.K., Rimal S. and Sangam H. (2009). Ageing of HDPE Geomembrane exposed to air, water and leachate at different Temperatures. Geotextiles and Geomembranes 27: 137 – 151.

Rowe R.K., Islam M. Z. and Hsuan Y.G. (2010). Effects of thickness on the aging of HDPE geomembranes. Journal of Geotechnical and Geoenvironmental Engineering ASCE, 136(2): 299 – 309.

Sangam H.P. and Rowe R.K. (2002). Effects of exposure conditions on the depletion of antioxidants from high-density Polyethylene (HDPE) Geomembranes. Canadian Geotechnical Journal 39: 1221 – 1230.

Swihart J. and Haynes J. (2002). Canal-Lining Demonstration Project Year 10 Final Report, R-02-03, Bureau of Reclamation, U.S. Department of the Interior, Denver, Colorado, U.S.A.

Tarnowski C. and Baldauf S. Ageing Resistance of HDPE-Geomembranes – Evaluation of Long-term Behavior under Consideration of Project Experiences, Web reference: http://www.gseworld.com/content/documents/articles/Ageing%20resistance%20of%20HDPE-geomembranes.pdf

Yako M.A., Koerner G.R., Koerner R.M. and Hsuan Y.G. (2010). Case history of a 20-year old exposed HDPE surface impoundment liner. Proc. of 9th Intl. Conf. on Geosynthetics, Guarujá, Brazil: 805 – 808.