Protecting the environment with geosynthetics

(53rd Karl Terzaghi Lecture)

R. Kerry Rowe

Professor and Canada Research Chair in Geotechnical and Geoenvironmental Engineering
GeoEngineering Centre at Queen's-RMC
Queen's University, Kingston, ON, Canada

Abstract

Design and construction related factors that affect leakage through geomembranes used either alone or in a composite liners are examined. The number of holes that can develop during construction and operation of a facility are discussed. The relationship between leakage through holes in a geomembrane and the hydraulic conductivity of the material above and below the liner is examined with particular emphasis on tailings above a single geomembrane on a relatively permeable subgrade and the unstressed zone beneath a wrinkle in a composite liner. It is shown that the leakage observed in the primary liners of 180 landfill cells can be explained by holed-wrinkles with a length consistent with those observed in the field and an appropriate choice of hydraulic conductivity of the clay liner below a holed-wrinkle(s). Leakage through GCL overlaps traversed by wrinkles is examined. The latest research into physical and chemical aging HDPE geomembranes liners is discussed in the context of the compatibility of the antioxidant package and resin with the solution to be retained, liner temperature, the nature of exposure, sustained tensile strains, and welds. The estimation of the service-life of a geomembrane based on immersion tests and simulated field conditions is examined in terms of antioxidant depletion, stress cracking, and the maximum allowable strain in a geomembrane. It is concluded that the service-life of a geomembrane may range from just a few years to many centuries.

Keywords

Geomembrane, GCL, leakage, service-life, HDPE, LLDPE, landfills, mining, ponds

DRAFT

which cannot be readily repaired or replaced, available evidence suggest a maximum allowable strain (from all sources) of 4%.

Seams/welds in a geomembrane were discussed as critical locations with respect to geomembrane service-life due to the substantial (up to 4-fold) magnification of the average tensile strain (higher demand) and faster degradation of the geomembrane (less resistance) compared to material away from the weld. More research is needed to better understand the aging of welds, but the discussion on the paper suggests that the potential for weld failure can be minimized by proper design and construction to minimize tensile strains in the geomembrane. The impact of failure adjacent to welds on leakage minimized by both minimizing wrinkles and using a composite liner with GCL.

Based on the discussion of longevity, it is concluded that the service-life of a geomembrane may range from just a few years to many centuries depending on the factors outlined above.

DRAFT

Acknowledgements

With many thanks to the GeoInstitute of ASCE for inviting me to present the 53rd Karl Terzaghi Lecture in Orlando, March 2017. The research presented in this paper was funded by the Natural Science and Engineering Research Council of Canada (NSERC). The author is very grateful to his colleagues in the GeoEngineering Centre at Queen's-RMC, especially Drs. Richard Brachman, Andy Take, Greg Siemens and Fady Abdelaal and Australian collaborator Ds. Malek Bouazza, A. El-Zein and R. McWatters. Industrial partners, Antarctic Department of Conservation and Management (Australian Antarctic Division), Canadian Nuclear Laboratories, Cetco, Naue, Ontario Ministry of Environment, Solmax-GSE, Terrafix Geosynthetics, and Thiel Engineering, for their support with various aspects of this research. Many past and present graduate students who co-authored papers that are referenced herein as well as …. Special thanks to Rick Thiel (Thiel Engineering) for Figures 2a, Abigail Gilson-Beck for Figure 2b, Ken Embree (Knight Piesold) for Figure 5a, Tony Bennett (Ontario Power Generation) for Figure 5b, Harvey McLeod (Klohn Crippen Berger) for Figure 5c, Ian Peggs (ICORP) for Figure 7, ... Special thanks also to Drs. Fady Abdelaal, Richard Brachman, … for assistance in preparation of the lecture and reviewing the draft paper. The views expressed herein are those of the author and not necessarily those of the many people who have assisted with the research or reviewed of the manuscript.

Notation

a	Area of a hole in GMB (m^2 or mm^2)
b	Half-width of a wrinkle (under operational conditions) (m)
C_B	Coefficient related to the shape of the edges of the hole in GMB (-)
C_{qo}	A contact quality factor established semi-empirically by Giroud et al. (1989b). C_{qo}= 0.21 for good and 1.15 for poor contact between the GMB and CL.
CL	Clay liner (either CCL or GCL)
CCL	Compacted clay liner
CQA	Construction quality assurance
D_x	D is the effective diameter of the soil particles and subscript x (10 and 60) denote the percent which is smaller.
ELLS	Electrical leak location survey
GCL	Geosynthetic clay liner
GLLS	Geosynthetic liner longevity simulator
GMB	Geomembrane
GTX	Geotextile
g	Acceleration due to gravity (9.8 m/s^2)
HAZ	Heat affected zone (adjacent to a weld)
h_a	Hydraulic head at the bottom of the liner (often zero)

h_d	Head loss across the liner; $h_d = h_w + H_L - h_a$ (m)
H_L	Thickness of clay liner (m)
h_w	Leachate head on liner (m)
HDPE	High density polyethylene
HP-OIT	High pressure oxidative induction time (ASTM D5885)
k	Hydraulic conductivity/permeability (m/s)
k_L	Hydraulic conductivity of clay liner (m/s)
k_{La}	Hydraulic conductivity of clay liner away from a wrinkle where there is direct contact and significant applied stress between the GMB and CL(m/s)
k_{Lb}	Hydraulic conductivity of clay liner below a wrinkle where there is no stress between the GMB and CL(m/s)
L	Length of longest connected wrinkle (m)
L_j	Length of jth connected wrinkle (m)
L_w	Length of wrinkle over and parallel to a GCL overlap(m)
lphd	Litres per hectare per day
LLDPE	Linear low density polyethylene
MSW	Municipal solid waste
n	Number of holes or holed-wrinkles per hectare in a GMB or porosity depending on context (-)
OIT	Oxidative induction time (see Std-OIT and HP-OIT)
PE	Polyethylene
PI	Plasticity index (-)
PL	Plastic limit (-)
Q	Leakage (m^3/s or lphd)
Q_B	Leakage (m^3/s or lphd) calculated using Bernoulli's equation [Eq. 1]
Q_{dc}	Leakage (m^3/s or lphd) calculated assuming direct contact using the Giroud (1997) equation [Eq. 2]
Q_{DL}	Leakage (m^3/s/ha or lphd) calculated from Darcy's law [Eq. 4b] assuming no GMB
Q_w	Leakage (m^3/s or lphd) calculated assuming a holed-wrinkle (i.e., a wrinkle with a hole) using the Rowe (1998) equation [Eq. 3]
Ra	Depletion adjustment factor [Ra = ratio of the depletion rate for a geomembrane immersed in leachate to that in the composite liner at a given temperature] (-)
r_o	Radius of a hole in a GMB (m)
SCR	Stress crack resistance typically obtained from the single point notched constant tensile load (SP-NCTL) test (ASTM D5397, Appendix)
SCR_m	tress crack resistance after physical aginf to a morphologically stable and representative value for the geomembrane
SCR_o	Initial stress crack resistance shortly after manufacture
Std-OIT	Standard oxidative induction time (ASTM D3895)
T	Liner temperature (^oC)
t_i	Time to OIT depletion [length of Stage I] (months or years)
t_{NF}	Time to nominal failure(months or years)
t_{SL}	Service-life of the geomembrane (months or years)
USA	United States of America
w_{opt}	Standard Proctor optimum water content
λ	L_w/L_j = proportion of a wrinkle over and parallel to GCL panel overlap (-)

Λ	(flow for a given overlap configuration) / (flow with a single GCL panel below the wrinkle) 9-).
θ	GMB/CL interface transmissivity (m^2/s)
η	Number of GCL panel overlaps crossed by a connected wrinkle
ρ_d	dry density of soil (kg/m^3)

References

Abdelaal, F.B. and Rowe, R.K. (2014) "Effect of high temperatures on antioxidant depletion from different HDPE geomembranes", Geotextiles and Geomembranes, 42(4): 284-301.

Abdelaal, F.B., and Rowe, R.K. (2015) "Durability of three HDPE GMBs immersed in different fluids at 85oC", ASCE Journal of Geotechnical and Geoenvironmental Engineering, 141(2), 04014106. http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0001234

Abdelaal, F.B and Rowe, R.K. (2017) "Effect of high pH found in low level radioactive waste leachates on the antioxidant depletion of a HDPE geomembrane", Journal of Hazardous, Toxic, and Radioactive Waste, 21(1); 10.1061/(ASCE)HZ.2153-5515.0000262, D4015001

Abdelaal, F.B. and Rowe, R.K. (2019a) "Degradation of a HDPE geomembrane without HALS in chlorinated water", Geosynthetics International, (Accepted 18/2/19; GI1266)

Abdelaal, F.B., Rowe, R.K. and Islam, M.Z. (2014) "Effect of leachate composition on the long-term performance of a HDPE geomembrane", Geotextiles and Geomembranes, 42(4):348-362. http://dx.doi.org/10.1016/j.geotexmem.2014.06.001

Abdelaal, F.B., Rowe, R.K. and Brachman, R.W.I. (2014) "Brittle rupture of an aged HDPE geomembrane at local gravel indentations under simulated field conditions", Geosynthetics International, 21 (1): 1-23. http://dx.doi.org/10.1680/gein.13.00031

Abdelaal, F.B., Rowe, R.K., and Brachman, R.W.I (2018) “Effect of liner temperature on the long term stress cracking of HDPE geomembranes under simulated field conditions”, 11th International Conference on Geosynthetics, Seoul, Korea, September.

Abdelaal, F.B., Morsy, M.S., & Rowe, R.K., (2019b). “Long-Term Performance of a HDPE Geomembrane Stabilized with HALS in Chlorinated Water”, Geotextiles and Geomembranes, (submitted)

Ashe, L. Rowe, R.K., Brachman, R.W.I. and Take, W.A. 2015. Laboratory study of down-slope erosion for ten different GCLs, ASCE Journal of Geotechnical and Geoenvironmental Engineering, 141 (1): 04014079: 1–8. http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0001191

ASTM D1238. Standard Test Method for Flow Rates of Thermoplastics by Extrusion Plastometer. Annual Book of ASTM Standards, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, USA.

ASTM D3895. Standard Test Method for Oxidative-induction Time of Polyolefins by Differential Scanning Calorimetry. Annual Book of ASTM Standards, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, USA.

ASTM D5397. Standard Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test. Annual Book of ASTM Standards, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, USA.

ASTM D5721 Practice for Air-Oven Aging of Polyolefin Geomembranes. Annual Book of ASTM Standards, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, USA.

ASTM D5885. Standard Test Method for Oxidative Induction Time of Polyolefin Geosynthetics by High-Pressure Differential Scanning Calorimetry. Annual Book of ASTM Standards, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, USA.

ASTM D7238 Test Method for Effect of Exposure of Unreinforced Polyolefin Geomembrane Using Fluorescent UV Condensation Apparatus. . Annual Book of ASTM Standards, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, USA.

Beck, A. (2014) Designing to minimize geomembrane leakage. Geosynthetic, August-September: 40-46.

Beck, A. (2015) Available technologies to approach zero leaks. Geosynthetics 2015, Portland, 10pp

Benson, C.H., Jo, H.Y. and Abichou, T. (2004). "Forensic analysis of excessive leakage from lagoons lined with a composite GCL." *Geosynthet. Int.*, 11(3), 242-252.

Brachman, R.W.I., Gudina, S. (2008). Geomembrane strains and wrinkle deformations in a GM/GCL composite liner. Geotextiles and Geomembranes, 26 (6), 488-497.

Brachman, R.W.I., Sabir, A. (2010). Geomembrane puncture and strains from stones in an underlying clay layer. Geotextiles and Geomembranes, 28 (4), 335–343.

Brachman, R.W.I., Rowe, R.K., Arnepalli, D.N., Dickinson, S., Islam, Z. and Sabir, A. (2008). "Development of an apparatus to simulate the ageing of geomembranes under chemical exposure, elevated temperatures and applied stresses", GEOAMERICAS 2008, Cancun, Mexico, March, pp. 444-451.

Brachman, R.W.I., Rowe, R.K. and Irfan (2014) "Short-Term Local Tensile Strains in HDPE Heap Leach Geomembranes from Coarse Overliner Materials", ASCE Journal of Geotechnical and

Geoenvironmental Engineering, 140(5): 04014011-1 to 04014011-8, http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.000

Brachman, R.W.I., Rentz, A., Rowe, R.K. and Take W.A. 2015. Classification and quantification of downslope erosion from a GCL when covered only by a black geomembrane, Canadian Geotechnical Journal, 52(4): 395-412 (10.1139/cgj-2014-0241)

Brachman, R.W.I, Joshi, P., and Rowe, R.K. (2016) “Hydraulic performance of overlapped geosynthetic clay liner seams requiring field-applied supplemental bentonite” ASCE Journal of Geotechnical and Geoenvironmental Engineering, 142 (12): 4016067-1 to 11; DOI: 10.1061/(ASCE)GT.1943-5606.0001566.

Brachman, R.W.I, Joshi, P. and Rowe, R.K. (2017) “A new laboratory apparatus for measuring leakage through geomembrane holes beneath mine tailings" Canadian Geotechnical Journal, 54(2):147-157.

Brachman, R.W.I., Rowe, R.K. and Take, W.A. 2018. Reductions in GCL overlap beneath an exposed geomembrane. ASCE Journal of Geotechnical and Geoenvironmental Engineering, 144 (12): 04018094 1-9. doi.org/10.1061/(ASCE)GT.1943-5606.0001985

Bradshaw, S.L., and Benson, C.H. 2014. Effect of Municipal Solid Waste Leachate on Hydraulic Conductivity and Exchange Complex of Geosynthetic Clay Liners. Journal of Geotechnical and Geoenvironmental Engineering, 140(4): 04013038. doi:10.1061/(ASCE)GT.1943-5606.0001050.

Brown, K.W., Thomas, J.C., Lytton, R.L., Jayawickrama, P. and Bahrt, S. 1987. Quantification of Leakage Rates Through Holes in Landfill Liners, U.S. EPA Report CR810940, Cincinnati, 147 p.

Chappel, M.J., Brachman, R.W.I., Take, W.A. and Rowe, R.K. 2012a. Large-scale quantification of wrinkles in a smooth, black, HDPE geomembrane, ASCE Journal of Geotechnical and Geoenvironmental Engineering, 138 (6): 671-679.

Chappel, M.J., Rowe, R.K., Brachman, R.W.I. and Take, W.A. 2012b. A comparison of geomembrane wrinkles for nine field cases, Geosynthetics International, 19(6): 453-469.

Chou, Y-C., Rowe, R.K. and Brachman, R.W.I. (2018) "Erosion of Silty Sand Tailings through a Geomembrane Defect under Filter Incompatible Conditions", Canadian Geotechnical Journal, Canadian Geotechnical Journal 55.11 (2018): 1564-1576.

Cooley, B.H., and Daniel, D.E. (1995). "Seam performance of overlapped geosynthetic clay liners." Proc., Geosynth. 1995, Nashville, TN, USA, IFAI, St. Paul, MN, USA, 691-705.

Daniel, D.E., Trautwein, S.J., and Goswami, P. (1997). "Measurement of hydraulic properties of GCLs using a flow box." In Testing and Acceptance Criteria for Geosynthetic Clay Liners, ASTM STP 1308, http://dx.doi.org/10.1520/STP1308-EB, 196-207.

Denis, R., Tan, D., and Cao D. (2012). A literature review on lifetime prediction of thin HDPE geomembranes in the exposed environment. Geosynthetics Asia 2012, *5th Asian Regional Conference on Geosynthetics*, Bangkok, Thailand.

Estornell, P., and Daniel, D.E. (1992). "Hydraulic conductivity of three geosynthetic clay liners." J. Geotech. Eng., 118(10), 1592-1606.

Ewais, A.M.R and Rowe, R.K. (2014a). Effect of ageing on the stress crack resistance of an HDPE geomembrane. Journal of Polymer Degradation and Stability, 109, pp. 194-208.

Ewais, A. M. R. and Rowe, R. K. (2014b). Degradation of 2.4 mm-HDPE geomembrane with high residual HP-OIT. 10th International Conference on Geosynthetics – 10th ICG, Berlin, Germany.

Ewais, A.M.R. and Rowe, R.K. (2014c). Effect of blown film process on initial properties of HDPE geomembranes of different thicknesses. Geosynthetics International, 21(1): 62-82.

Ewais, A. M.R., Rowe, R.K., Brachman, R.W.I., and Arnepalli D.N. (2014a). "Service-life of a HDPE GMB under simulated landfill conditions at 85ºC" ASCE Journal of Geotechnical and Geoenvironmental Engineering, 140(11): 040aw14060: 1-13, DOI: http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0001164

Ewais, A.M.R., Rowe, R.K., Rimal, S. and Sangam, H.P. (2018) "17-year elevated temperature study of HDPE geomembrane longevity in air, water and leachate", Geosynthetics International, 25(5), 525-544.

Francey, W. and Rowe, R.K. (2017) "Reduction in geomembrane seam oxidative induction time for aged welds performed at varying ambient temperatures", GeoOttawa 2017, Canadian Geotechnical Conference, Ottawa, October,

Gilson-Beck, A. 2019. Controlling leakage through installed geomembranes, *Geotextiles and Geomembranes*, 47 (in press)

Giroud, J.P. 1997. Equations for calculating the rate of liquid migration through composite liners due to geomembrane defects, Special Issue on Liquid Migration Control Using Geosynthetic Liner Systems, Geosynthetics Int., 4 (3-4): 335-348.

Giroud, J.P. (2005). Quantification of geosynthetic behavior. Geosynthetics International, 12 (1), 2-27.

Giroud, J.P. 2016. Leakage control using geomembrane liners. Soils and Rocks, 39(3): 213-235.

Giroud, J.P. and Bonaparte, R. 1989a. Leakage through liners constructed with geomembranes - Part I: Geomembrane liners, Geotextiles and Geomembranes, 8: 27-67, DOI: 10.1016/0266-1144(89)90009-5

Giroud, J.P. and Bonaparte, R. 1989b Leakage through liners constructed with geomembranes - Part II: Composite liners, Geotextiles and Geomembranes, 8: 71-111, DOI: 10.1016/0266-1144(89)90022-8.

Giroud, J.P. and Bonaparte, R. 2001. Geosynthetics in liquid-containing structures, Chapter 26 of Geotechnical and Geoenvironmental Engineering Handbook, Kluwer Academic Publishing, Norwell, 789-824.

Giroud, J.P. and Morel, N. 1992. Analysis of geomembrane wrinkles, Geotextiles and Geomembranes, 11(3): 255 276 (Erratum: 12(4): 378).

Giroud, J.P., Tisseau, B., Soderman, K.L., Beech, J.F. (1995). Analysis of strain concentration next to geomembrane seams. Geosynthetics International, 2 (6), 1049–1097.

GRI-GM13 (2016). Standard Specification for Test Methods, Test Properties and Testing Frequency for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes: GRI Test Method Geomembrane 13, Revision 14, Geosynthetic Research Institute, Folsom, Pa.

GRI-GM19. 2011. Standard Specification for Seam Strength and Related Properties of Thermally Bonded Polyolefin Geomembranes., Revision 6: October 3, 2011. Geosynthetic Research Institute, Folsom, Pennsylvania, USA. www.geosynthetic-institute.org

Holtz, R. D. (2017). 46th Terzaghi lecture: geosynthetic reinforced soil: from the experimental to the familiar, https://doi.org/10.1061/(ASCE)GT.1943-5606.0001674

Hsuan, Y.G. (2000). Database of field incidents used to establish HDPE geomembrane stress crack resistance specifications. Geotextile and Geomembrane, 18(1): 1–22.

Hsuan, Y.G. (2013). Innovation of polyolefin resins used in Geosynthetics over the past 25 years. Proceedings of Geosynthetics 2013 Conference, Long Beach, CA, USA. CD-ROM, 8p.

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

Jayawickrama, P., Brown, K.W., Thomas, J.C. and Lytton, R.L. 1988. Leakage rates through flaws in membrane liners. ASCE Journal of Environmental Engineering, 114(6):1401-1419.

Joshi, P., Rowe, R.K. and Brachman, R.W.I (2017a) "Physical and hydraulic response of geomembrane wrinkles underlying saturated fine tailings", Geosynthetics International, 24(1):82-94, http://dx.doi.org/10.1680/jgein.16.00017

Joshi, P., Brachman, R.W.I and Rowe, R.K. (2017b) "Hydraulic performance of GCL seams without field-applied supplemental bentonite below a geomembrane wrinkle", ASCE Journal of Geotechnical and Geoenvironmental Engineering, 143(9): 04017086-1 to 10, doi/10.1061/(ASCE)GT.1943-5606.0001756.

Joshi, P., Rowe, R.K. and Brachman, R.W.I (2018) "Hydraulic performance of GCL seams with factory-applied powered bentonite below a geomembrane wrinkle" Environmental Geotechnics, 5(5): 263-270http://dx.doi.org/10.1680/jenge.16.00027.

Kavazanjian, E., Andresen, J., Gutierrez, A. (2017). Experimental evaluation of HDPE geomembrane seam strain concentrations. Geosynthetics International, 24 (4), 333-342.

Kendall, P.M., and Austin, R.A. (2014). "Investigation of GCL overlap techniques using a large scale flow box." Proc. 7th Int. Congress Env. Geotech., Melbourne, 746-753.

Knuuttila, H., Lehtinen, A., and Nummila-Pakarinen, A. (2004). Advanced Polyethylene Technologies-Controlled Material Properties. Advances in Polymer Science, 169: 13-27.

Koerner, R. M. (2000). Emerging and future developments of selected geosynthetic applications; The 32nd Terzaghi lecture. *Journal of Geotechnical and Geoenvironmental Engineering, 126*(4), 293-306.

Koerner, R.M. (2012). Designing with Geosynthetics. 6th Edition, Xlibris Corporation 528p.

Koerner, R.M. and Hsuan, Y.G. (2003). Lifetime prediction of polymeric geomembranes used in new dam construction and dam rehabilitation. Proceedings of State Dam Safety, Officials Conference, Lake Harmony, Pennsylvania, June 4-6, 2003, 16

Koerner, G. R., Eith, A. W., Tanese, M. (1999). "Properties of exhumed HDPE field waves." Geotextiles and Geomembranes, 17(4), 247-261.

Koerner, R. M., Hsuan, Y. G., & Koerner, G. R. (2016). Lifetime predictions of exposed geotextiles and geomembranes. Geosynthetics International, 24(2), 198-212.

Mitchell, J.K. (1991) Conduction phenomena: from theory to geotechnical practice, Géotechnique, 41(3):299-340.

MOECC (2012) Landfill standards: a guideline on the regulatory and approval requirements for new or expanding landfilling sites. Ontario Regulation 232/98 under Part V of the Ontario (Canada) Environmental Protection Act, Government printer.

Müller, W. W. (2007). HDPE geomembranes in geotechnics. Berlin: Springer

Müller, W. W. and Jakob, I., 2002. Oxidative resistance of high-density polyethylene geomembranes" Polymer Degradation and Stability, 79 (1). 161-172.

Peggs, I.D., Schmucker, B. and Carey, P. (2005). Assessment of maximum allowable strains in polyethylene and polypropylene geomembranes. In Waste Containment and Remediation, 1-16.

Peggs, I.D, Gassner, F., Scheirs, J., Tan, D., Noval Arango, A.M., and Burkard, B. (2014) "Is there a resurgence of stress cracking in HDPE geomembranes", 10th International Conference on Geosynthetics, Berlin, 10p.

Pelte, T., Pierson, P. and Gourc, J.P. (1994) Thermal analysis of geomembranes exposed to solar radiation. Geosynthetics International, 1, No. 1, 21-44.

Rentz, A., Take W.A., Brachman, R.W.I. and Rowe, R.K., 2016. Effect of geomembrane colour and cover soil on solar-driven down slope bentonite erosion from a GCL, Geosynthetics International, 23(4): 257–270. http://dx.doi.org/10.1680/jgein.15.00050

Rentz, A., Brachman, R.W.I, Take, W.A. and Rowe, R.K. (2017) Comparison of wrinkles in white and black HDPE geomembranes. ASCE Journal of Geotechnical and Geoenvironmental Engineering, 143(8): 04017033-1 to 8; DOI: 10.1061/(ASCE)GT.1943- 5606.0001715.

Rimal, S. and Rowe, R.K. (2009). "Diffusion modelling of OIT depletion from HDPE geomembrane in landfill applications", Geosynthetics International, 16(3):183-196.

Rowe, R.K. (1998). Geosynthetics and the minimization of contaminant migration through barrier systems beneath solid waste, Proceedings of the 6th International Conference on Geosynthetics, Atlanta, Ga., 25–29 March 1998. Industrial Fabrics Association International, St. Paul, Minn. Vol., 1:27-103.

Rowe, R.K. (2005). Long-term performance of contaminant barrier systems, 45th Rankine Lecture, Geotechnique, 55(9): 631-678. DOI: 10.1680/geot.2005.55.9.631

Rowe, R.K. (2011). "Systems engineering the design and operations of municipal solid waste landfills to minimize leakage of contaminants to groundwater", Geosynthetics International, 16(6): 391-404.

Rowe, R.K. (2012). Short and long-term leakage through composite liners, 7th Arthur Casagrande Lecture, Canadian Geotechnical Journal, 49(2): 141-169. DOI: https://doi.org/10.1139/t11-092

Rowe, R. K. (2014). Performance of GCLs in liners for landfill and mining applications. Environmental Geotechnics 1(1), 3-21.

Rowe, R.K. (2016). Some consideration with respect to the long term performance of multicomponent GCLs. GeoAmericas 2016, Miami, USA.

Rowe, R.K. (2017) ASCE's video recording of the 53rd Karl Terzaghi Lecture: Protecting the environment with geosynthetics. https://www.youtube.com/watch?v=vyLpkObB1a8

Rowe, R.K. (2018a) Environmental geotechnics: looking back, looking forward (16th Croce Lecture), Italian Geotechnical Journal, 4/2018, DOI:10.19199/2017.4.0557-1405.47

Rowe, R.K. (2018b). Geosynthetic liners: Perceptions and misconceptions, Keynote lecture, 11th International Conference on Geosynthetics, Seoul, Korea, September.

Rowe, R.K. and Abdelaal, F.B. (2016) "Antioxidant depletion in HDPE Geomembrane with HALS in low pH heap leach environment", 53(10):1612-1627, Canadian Geotechnical Journal, DOI: 10.1139/cgj-2016-0026.

Rowe, R.K. and AbdelRazek, A.Y. (2019) "Effect of interface transmissivity and hydraulic conductivity on contaminant migration through composite liners with wrinkles or failed seams", *Canadian Geotechnical Journal*, (in press)

Rowe, R.K. and Ewais, A.M.R. (2014) "Antioxidant depletion from five geomembranes of same resin but of different thicknesses immersed in leachate", Geotextiles and Geomembranes, 42(5): 540-554 http://dx.doi.org/10.1016/j.geotexmem.2014.08.001

Rowe, R.K. and Ewais, A.R. (2015). “Ageing of exposed geomembranes at locations with different climatologicalcon ditions”, Canadian Geotechnical Journal, 52 (3):326-343 (http://dx.doi.org/10.1139/cgj-2014-0131)

Rowe, R.K. and Francey, W. (2018) “Effect of Dual Track Wedge Welding at 30°C Ambient Temperature on Post-weld Geomembrane Oxidative Induction Time”, 11th International Conference on Geosynthetics, Seoul, Korea, September.

Rowe, R.K. and Islam, M.Z. (2009). “Impact on landfill liner time-temperature history on the service-life of HDPE geomembranes”, Waste Management, 29: 2689-2699.

Rowe R.K. and Li, T-K. 2016a. Preliminary laboratory simulation of self-healing of fully penetrating hole in GCLs with applied stress, 3rd Pan-American Conference on Geosynthetics, GeoAmerica’s 2016, Miami Beach, USA, April.

Rowe R.K. and Li, T-K. 2016b. A preliminary study of bentonite self-healing of slits in a GCL on full hydration, GeoChicago, Chicago, USA, August, GSP275: 116-125.

Rowe, R.K. and Rimal, S. (2008a). “Depletion of antioxidants from an HDPE geomembrane in a composite liner”, ASCE Journal of Geotechnical and Geoenvironmental Engineering, 134(1):68-78.

Rowe, R.K. and Rimal, S. (2008b). “Ageing of HDPE geomembrane in three composite liner configurations”, ASCE Journal of Geotechnical and Geoenvironmental Engineering, 134(7) 906-916.

Rowe, R.K and Sangam, H.P. (2002). “Durability of HDPE geomembranes”, Geotextiles and Geomembranes, 20 (2):77-95.

Rowe, R.K. and Shoaib, M. (2017) " Effect of brine on long-term performance of four HDPE GMBs”, Geosynthetics International, 24 (5):508-523, https://doi.org/10.1680/jgein.17.00018

Rowe, R.K. and Shoaib, M. (2018) " Durability of HDPE geomembrane seams immersed in brine for three years", ASCE Journal of Geotechnical and Geoenvironmental Engineering, 144 (2) (February 2018), https://doi.org/10.1061/(ASCE)GT.1943-5606.0001817,

Rowe, R.K. and Shoaib, M. (2017) "Long-term performance HDPE geomembrane seams in MSW leachate", Canadian Geotechnical Journal, 54(12): 1623-1636, https://doi.org/10.1139/cgj-2017-0049

Rowe, R.K. and Yu, Y. (2018b) Tensile Strains in Geomembrane Landfill Liners. Keynote lecture GeoShanghai 2018, Shanghai, China, May, 8:1-10

Rowe, R.K., Caers, C.J., Reynolds, G. and Chan, C. (2000). Design and construction of barrier system for the Halton Landfill. Canadian Geotechnical Journal, 37(3):662-675.

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(3): 536-550.

Rowe R.K., Quigley R.M., Brachman R.W.I, Booker J.R. (2004). Barrier systems for waste disposal facilities. London: E & FN Spon; 2004. 587p.

Rowe, R.K., Islam, M.Z. and Hsuan, Y.G. (2008). "Leachate chemical composition effects on OIT depletion in HDPE geomembranes", *Geosynthetics International*, 15(2):136-151.

Rowe, R.K., Rimal, S. and Sangam, H.P. (2009). Ageing of HDPE geomembrane exposed to air, water and leachate at different temperatures. Geotextiles and Geomembranes, 27(2), pp. 131-151.

Rowe, R.K., Bostwick, L.E. and Thiel, R. (2010a). "Shrinkage characteristics of heat-tacked GCL seams", Geotextiles and Geomembranes, 28(4):352-359.

Rowe, R.K., Islam, M.Z., Brachman, R.W.I., Arnepalli, D.N. and Ewais, A.R. (2010b). "Antioxidant depletion from a high density polyethylene geomembrane under simulated landfill

conditions", ASCE Journal of Geotechnical and Geoenvironmental Engineering, 136(7): 930-939.

Rowe, R.K, Islam, M.Z. and Hsuan, Y.G. (2010c). "Effect of thickness on the ageing of HDPE geomembranes", ASCE Journal of Geotechnical and Geoenvironmental Engineering, 136(2):299-309.

Rowe, R.K., Chappel, M.J., Brachman, R.W.I. and Take, W.A. (2012a). Field monitoring of geomembrane wrinkles at a composite liner test site, Canadian Geotechnical Journal, 49(10): 1196-1211.

Rowe, R.K., Yang, P., Chappel, M.J., Brachman, R.W.I. and Take, W.A. (2012b). Wrinkling of a geomembrane on a compacted clay liner on a slope, Geotechnical Engineering, Journal of the South East Asian Geotechnical Society, 43(3): 11-18.

Rowe, R.K, Brachman, R.R.W., Irfan, H., Smith, M.E., and Thiel, R. (2013a) Effect of underliner on geomembrane strains in heap leach applications. *Geotextiles and Geomembranes*, 40: 37-47.

Rowe, R.K., Abdelaal, F.B. and Brachman, R.W.I. (2013b) "Antioxidant depletion from an HDPE geomembrane with a sand protection layer", Geosynthetics International, 20(2):73-89. http://dx.doi.org/10.1680/gein.13.00003

Rowe, R.K., Take, W.A., Brachman, R.W.I, and Rentz, A., (2014a). Field observations of moisture migration on GCLs in exposed liners, 10th International Conference on Geosynthetics, Berlin, September CD Rom Paper #86, 8p.

Rowe, R.K., Ashe, L.E., Take W.A., and Brachman, R.W.I. (2014b) Factors affecting the down-slope erosion of bentonite in a GCL. *Geotextiles and Geomembranes*, 42(5): 445-456 http://dx.doi.org/10.1016/j.geotexmem.2014.07.002

Rowe, R.K., Abdelaal, F.B. and Islam, M.Z. (2014c) “Aging of HDPE geomembrane of three different thicknesses”, ASCE Journal of Geotechnical and Geoenvironmental Engineering, 140(5): 4014005-1 to 4014005-11, DOI: 10.1061/(ASCE)GT.1943-5606.0001090

Rowe, R.K., Brachman, R.W.I, Take, W.A, Rentz, A. and Ashe, L.E., (2016a). Field and laboratory observations of down-slope bentonite migration in exposed composite liners, Geotextiles and Geomembranes, 44(5): 686-706,dx.doi.org/10.1016/j.geotexmem.2016.05.004

Rowe, R.K., Rentz, A., Brachman, R.W.I. and Take W.A. (2016b). Effect of GCL type on down-slope bentonite erosion in an exposed liner. ASCE Journal of Geotechnical and Geoenvironmental Engineering, 142(12) 4016074-1 to 10; DOI: 10.1061/(ASCE)GT.1943-5606.0001565

Rowe, R.K., Joshi, P., Brachman, R.W.I and McLeod, H. (2017a) “Leakage through holes in geomembranes below saturated tailings”, ASCE Journal of Geotechnical and Geoenvironmental Engineering, 143(2):4016099-1 to 10 ;DOI: 10.1061/(ASCE)GT.1943-5606.0001606.

Rowe, R.K., Brachman, R.W.I., Hosney, M.S. Take, W.A. and Arnepalli, D.N. (2017b) “Insight into hydraulic conductivity testing of GCLs exhumed after 5 and 7 years in a cover”, Canadian Geotechnical Journal, 54(8): 1118-1138, https://doi.org/10.1139/cgj-2016-0473

Rowe, R.K., Brachman, R.W.I. and Take, W.A. (2018). Field measurements of overlap reductions for two reinforced fabric-encased GCLs. Canadian Geotechnical Journal, 55(5): 631-639. https://doi.org/10.1139/cgj-2017-0375

Rowe, R.K., Garcia, J.D., Brachman, R.W.I., and Hosney, M.S. 2019a. “Hydraulic and Chemical Performance of Geosynthetic Clay Liners Isothermally Hydrated from Silty Sand Subgrade”. Geotextiles and Geomembranes, (tentatively accepted)

Rowe, R.K., Morsy, M.S. and Ewais, A.M.R. (2019b) “A Representative Stress Crack Resistance for Polyolefin Geomembranes Used in Waste Management”, Waste Management, (Submitted 26/2/2019; WM-19-534).

Rowe, R.K., Priyanto, D. and Poonan, R. (2019c) “Factors affecting the design life of HDPE geomembranes in an LLW disposal facility”, WM2019 Conference, March 3 – 7, 2019, Phoenix,

Sangam, H.P. and Rowe, R.K (2002). “Effects of exposure conditions on the depletion of antioxidants from HDPE geomembranes”, Canadian Geotechnical Journal, 39(6):1221-1230.

Scheirs, J. (2000). Compositional and Failure Analysis of Polymers: A Practical Approach, John Wiley & Sons, Ltd, Chichester, UK, pp. 766.

Scheirs, J. (2009). A guide to polymeric geomembranes: A practical approach. John Wiley and Sons, Ltd, Australia, 572 p.

Seeger, S. and Müller, W. (1996a). Limits of stress and strain: design criteria for protective layers for geomembranes in landfill liner systems, geosynthetics: Applications design and construction, A.A. Balkema, Rotterdam, Netherlands, pp. 153-157.

Seeger, S. and Müller, W. (1996b). Requirement and Testing of Protective Layer Systems for Geomembranes. Geotextiles and Geomembranes, 14(7-8): 365-376.

Shackelford, C.D. 2014. The ISSMGE Kerry Rowe Lecture: The role of diffusion in environmental geotechnics. Canadian Geotechnical Journal, (51): 1219-1242.

Soong, T.-Y. and Koerner, R.M. (1998) Laboratory study of high density polyethylene geomembrane waves, Proceeding of Sixth International Conference on Geosynthetics, Atlanta, USA, Vol. 1, pp. 301-306.

Take, W.A., Chappel, M.J., Brachman, R.W.I. and Rowe, R.K. (2007). Quantifying geomembrane wrinkles using aerial photography and digital image processing, Geosynthetics International, 14(4) 219-227.

Take, W.A., Rowe, R.K , Brachman, R.W.I., and Arnepalli, D.N. (2015a). Thermal exposure conditions for a composite liner with a black geomembrane exposed to solar radiation, Geosynthetics International, 22(1): 93-109.

Take, W.A., Brachman, R.W.I., and Rowe, R.K. (2015b). Observations of bentonite erosion from solar-driven moisture migration in GCLs covered only by a black geomembrane, Geosynthetics International, 22(1): 78-92.

Tarnowski, C. and Baldauf, S. (2006). Ageing resistance of HDPE-geomembranes - Evaluation of long-term behavior under consideration of project experiences. Geosynthetics, J. Kuwano & J. Kosaki (eds), Millpress, Rotterdam, N.L.D., pp. 359-362.

Thiel, R. & Richardson, G. (2005). Concern for GCL shrinkage when installed on slopes, JGRI-18 at GeoFrontiers, Folsom, PA, USA.

Thiel, R. and Thiel, C. (2009). GCL shrinkage - A possible solution, Geosynthetics, February/March 2009: 10-21.

Thiel, R., Giroud, J.P., Erickson, R., Criley, K. and Bryk, J. (2006). Laboratory measurements of GCL shrinkage under cyclic changes in temperature and hydration conditions, 8th International Conference on Geosynthetics, Yokohama, Japan 1: 21-44.

Tian, K., Benson, C. H., Tinjum, J. M., & Edil, T. B. (2017). Antioxidant depletion and service life prediction for HDPE geomembranes exposed to low-level radioactive waste leachate. Journal of Geotechnical and Geoenvironmental Engineering, 143(6), 04017011.

Touze-Foltz, N., Rowe, R.K. and Duquennoi, C. (1999). Liquid flow through composite liners due to geomembrane defects: Analytical solutions for axi-symmetric and two-dimensional problems, Geosynthetics International, 6(6):455-479.

Touze-Foltz, N., Schmittbuhl, J., and Memier, M. (2001) Geometric and spatial parameters of geomembrane wrinkles on large scale model tests. Proceedings of Geosynthetics 2001, Portland, USA, pp. 715-728.

Viebke, J., Elble, E., Ifwarson, M. and Gedde U.W. (1994). Degradation of unstabilized medium-density polyethylene pipes in hot-water applications. Polymer Engineering and Science, 34(17), pp. 1354-1361.

Table 1 Grain size of underliner (UL), number short-term punctures (a ~2 mm^2) and leakage if a 0.3m head could be maintained for 1.5 mm HDPE except * (based on data from research reported by Rowe et al. 2013 but with additional interpretation)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
UL	D_{20} (mm)	D_{40} (mm)	D_{60} (mm)	D_{80} (mm)	D_{100} (mm)	# holes (ha^{-1})	Leakage^ (lphd)	Max tensile strain+ %
S1	7	10.1	19	20.1	38	300,000	9.9x10^7	40 S
S2	0.11	3.7	10.7	30	80	170,000	5.5x10^7	38 S
S2*	0.11	3.7	10.7	30	80	100,000	3.3x10^7	31 S
S3	0.11	0.5	2.1	10.0	80	0	-	13-14 S; 9 C
S4	0.09	0.23	1	3.05	10	0	-	11 C
S5	0.075	0.1	0.18	0.3	2	0	-	15-18 C
S6			<0.075	0.22	0.9	0	-	13 C
GCL/S5		GCL w_c = 86 → 64%				0	-	14-21C
GCL/S5		GCL w_c = 7 → 55%				0	-	12-18 C
CCL (w_{opt})		CCL w_c = 12.2→ 10.7%				0	-	18-25 C
CCL (w_{opt} + 4%)		CCL w_c = 16.1→ 12.4%				0	-	33-36 C
CCL (w_{opt} + 4%)		One 35 mm gravel in CCL				0	-	18 S$

* LLDPE; Columns 2 gives the particle size for which 20% of the dry mass of soil was smaller (similar definitions for D_{40} etc.) ^ Short-term leakage calculated from Bernoulli's equation assuming a sustained head of 0.3 m on the geomembrane. + Maximum tensile strain due to an indentation: S indicates the strain was from gravel in the subgrade; C indicates the strain was from gravel in the cover soil. $ Brachman and Sabir (2010)

Table 2. Overliner Grain Size and maximum tensile strain from overliner for a range of stresses (Underliner: S5 from Table 1).

Overliner	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	D_{85} (mm)	C_u (-)	C_c (-)	Applied stress (kPa) 500	1000	2000	3000
							Max tensile strain+ %			
OL1	2	8.8	18	30	9.0	2.2	6	8	18	27
OL2	0.18	1.9	8	17	44	2.5			12	15
OL3	0.05	0.23	2	10.1	40	0.5			9	12
Sand/OL1	2	8.8	18	30	9.0	2.2				< 2

Draft

Table 3. Calculated leakage through five 10 mm-diameter holes in a geomembrane underlain by a material with hydraulic conductivity, k_s, and overlain by a material with hydraulic conductivity, k_c for a 5m head above the geomembrane (Figure 6a, b and c). Rounded to 2 significant digits.

(1)	(2)	(3)	(4)	(5)
k_C (m/s)	k_S (m/s)	Q (lphd)	Q (mm/d)	Figure
∞	∞	200,000	20	6a
∞	$1x10^{-4}$	200,000	20	6b
∞	$1x10^{-6}$	80,000	8	6b
∞	$1x10^{-8}$	810	0.08	6b
$1x10^{-5}$	$1x10^{-6}$	70,000	7	6c
$1x10^{-5}$	$1x10^{-8}$	800	0.08	6c
$1x10^{-6}$	$1x10^{-8}$	790	0.08	6c

Table 4. Experimentally observed leakage, Q, through hole (r_o= 5 mm unless otherwise noted) hole in 1 mm-thick LLDPE geomembrane with tailing having hydraulic conductivity, k_T, above the geomembrane and subgrade with hydraulic conductivity, k_S, below the geomembrane subject to head, h, and effective stress at bottom of tailings of σ_v'. Table compiled from data published by Rowe et al. (2017). Leakage rounded to 2 significant figures

(1)	(2)	(3)	(4)	(5)	(6)
k_T (m/s)	k_S (m/s)	σ_v' (kPa)	h (m)	Q_1^ (lpd)	Q+ (lphd)
$5.4x10^{-7}$	$7x10^{-6}$ (est)	50	20	1.2	6.0
$4.2x10^{-7}$	$3.8x10^{-6}$	500	50	2.7	14
$1.1x10^{-7}$	$6.9x10^{-7}$	1500	150	4.5*	23
$1.6x10^{-6}$	$6.9x10^{-7}$	1500	150	7	35
$1.1x10^{-7}$	$6.9x10^{-7}$	1500	150	4.5*	23
$2.9x10^{-8}$	$6.9x10^{-7}$	1500	150	0.5	2.5
$1.1x10^{-7}$	$1x10^{-2}$ (est)	1500	150	> 2000#	> 10000
$1.1x10^{-7}$	$1.2x10^{-5}$	1500	150	4	20
$1.1x10^{-7}$	$6.9x10^{-7}$	1500	150	4.5*	23
$1.1x10^{-7}$	$1.1x10^{-7}$	1500	150	3	15
Results below are for r_o= 0.75 mm					
$1.1x10^{-7}$	$1x10^{-2}$ (est)	1500	150	0.08	0.40
$1.1x10^{-7}$	$6.9x10^{-7}$	1500	150	0.005	0.025

* Average of results from four test with leakages of 2.4, 4.5, 5 and 6 lpd
^ Measured leakage for a single hole under conditions indicated
+ inferred for results, Q_1, for a single hole assuming 5 holes/ha
# Exceeded 2000 lpd and associate with piping of tailings through hole

Draft

Table 5. Probability of exceeding a given leakage through primary liner based on field data for NY double lined landfills (based on data published by Beck 2015)

(1)	(2)	(3)
Leakage	Probability leakage ≥ leakage indicated	
(lphd)	no ELLS	with ELLS
10	90%	82%
20	83%	72%
40	65%	58%
60	52%	47%
80	45%	33%
100	38%	25%
150	30%	5%
190	19%	3%
300	8%	
500	5%	
800	<2%	

Draft

Table 6. Calculated leakage through five 10 mm-diameter holes in a geomembrane (GMB), of which one hole is in any wrinkle of length L, underlain by a material with hydraulic conductivity, k_{La}, where the geomembrane is in direct contact with the clay liner and k_{Lb} in the unstressed zone beneath the wrinkle. h_w=0.3 m, k_C >1x10$^{-2,}$ (m/s), H_L (CCL) =0.6 m, H_L (GCL) =0.01 m, compressed ($\sigma_v \geq$ 100 kPa) 2b=0.1 m. Calculated numbers rounded to 2 significant digits.

(1) Case	(2) Eq.	(3) L (m)	(4) θ (m^2/s)	(5) k_{La} (m/s)	(6) k_{Lb} (m/s)	(7) Q (lphd)
GMB on very permeable subgrade	1	0	-	1x10^{-3}	-	49,000
CCL alone	4	0	-	1x10^{-9}	-	1,300
GMB/CCL direct poor contact	2	0	1x10^{-7}	1x10^{-9}	-	15
GMB/CCL direct good contact	2	0	2x10^{-8}	1x10^{-9}	-	3
GMB/CCL wrinkle, poor contact	3 → 4	1000	1x10^{-7}	1x10^{-9}	1x10^{-9}	1300
GMB/CCL wrinkle, good contact	3	1000	2x10^{-8}	1x10^{-9}	1x10^{-9}	910
GMB/CCL wrinkle, good contact	3	1000	2x10^{-8}	5x10^{-10}	1x10^{-9}	650
GMB/CCL wrinkle, poor contact	3	200	1x10^{-7}	1x10^{-9}	1x10^{-9}	400
GMB/CCL wrinkle, good contact	3	200	2x10^{-8}	1x10^{-9}	1x10^{-9}	180
GMB/CCL wrinkle, good contact	3	200	2x10^{-8}	5x10^{-10}	1x10^{-9}	130
GMB/CCL wrinkle, poor contact	3	10	1x10^{-7}	1x10^{-9}	1x10^{-9}	14
GMB/CCL wrinkle, good contact	3	10	2x10^{-8}	1x10^{-9}	1x10^{-9}	9
GMB/CCL wrinkle, good contact	3	10	2x10^{-8}	5x10^{-10}	1x10^{-9}	6
GCL alone	4	0	-	5x10^{-11}	-	1,300
GMB/GCL direct poor contact	2	0	1x10^{-7}	5x10^{-11}	-	5.5
GMB/GCL direct good contact	2	0	2x10^{-8}	5x10^{-11}	-	1
GMB/GCL wrinkle, poor GCL & contact	3	1000	1x10^{-10}	5x10^{-11}	4x10^{-9}	1100
GMB/GCL wrinkle, good contact	3	1000	3x10^{-11}	5x10^{-11}	4x10^{-9}	1100
GMB/GCL wrinkle, poor contact	3	1000	1x10^{-10}	5x10^{-11}	4x10^{-10}	140
GMB/GCL wrinkle, good contact	3	1000	3x10^{-11}	5x10^{-11}	4x10^{-10}	130
GMB/GCL wrinkle, good contact	3	1000	3x10^{-11}	5x10^{-11}	5x10^{-11}	34
GMB/GCL wrinkle, poor GCL & contact	3	200	1x10^{-10}	5x10^{-11}	4x10^{-9}	220
GMB/GCL wrinkle, good contact	3	200	3x10^{-11}	5x10^{-11}	4x10^{-9}	220
GMB/GCL wrinkle, poor contact	3	200	1x10^{-10}	5x10^{-11}	4x10^{-10}	29
GMB/GCL wrinkle, good contact	3	200	3x10^{-11}	5x10^{-11}	4x10^{-10}	25
GMB/GCL wrinkle, good contact	3	200	3x10^{-11}	5x10^{-11}	5x10^{-11}	7
GMB/GCL wrinkle, good contact	3	10	3x10^{-11}	5x10^{-11}	4x10^{-7}	1100
GMB/GCL wrinkle, poor GCL & contact	3	10	1x10^{-10}	5x10^{-11}	4x10^{-9}	11
GMB/GCL wrinkle, poor contact	3	10	1x10^{-10}	5x10^{-11}	4x10^{-10}	1.4

Draft

Table 7. Summary of permeation tests on seams below wrinkles at 250 kPa (modified from Brachman et al. 2016 and Joshi et al. 2017b, 2018) under a hydraulic head of 0.3 m and an applied stress of 250 kPa to the gavel drainage layer above the geomembrane. Rounded to 2 significant digits.

GCL type [a]	Orientation with wrinkle	Overlap width	Supplemental bentonite	Λ [b]
(1)	(2)	(3)	(4)	(5)
	Single panel (no seam) reference			1
GCL2	Parallel	50	None	>200,000
GCL2	Parallel	150	400 g/m	0.2
GCL4	Parallel	150	Groove	1.8
GCL2	Perpendicular base case [c]			0.8
GCL1&2	Perpendicular	150	400 g/m	2.3 [d]
GCL4	Perpendicular	150	Groove	2.5 [e]
GCL3	Perpendicular	150	Groove	370 [f]
GCL5	Perpendicular	300	400 g/m	1
GCL5	Perpendicular	300	Impregnated	2300 [g]
GCL6	Perpendicular	300	Impregnated	4.6

Notes: [a] GCL1: fine granular bentonite, a woven thermally treated carrier geotextile. GCL2: fine granular bentonite, a woven/nonwoven (scrim reinforced) thermally treated carrier geotextile. GCL3: coarse granular bentonite, a woven carrier geotextile. GCL4: coarse granular bentonite, a nonwoven carrier geotextile. GCL5: powdered bentonite, a woven/nonwoven (scrim reinforced) thermally treated carrier geotextile. GCL6 powdered bentonite, a woven thermally treated carrier geotextile. [b] Λ = (flow in Test) / (flow with no seam). [c] 0.15 m of panel over single panel below wrinkle and no preferential path through the single panel. [d] average of 3 tests (Λ:0.8, 2.7, 3.3). [e] average of 3 tests (Λ: 2.0, 2.4, 3.0). [f] average of 2 tests (Λ: 330, 410). [g] average of 2 tests (Λ: 1500, 3100)

Draft

Table 8. Effect of various factors on length of Stage I, t_I, and time to nominal failure, t_{NF}, of HDPE geomembranes immersed in fluid. Numbers rounded to 2 significant digits.

Row	Immersion fluid	T (°C)	GMB & thickness (mm)	Std-OIT$_o$ (min)	HP-OIT$_o$ (min)	SCR$_o$ (hrs)	$t_I^{\#}$ (yrs)	t_{NF}^{*} (yrs)	t_{NF} Ratio (-)	Ref
	Effect of geomembrane properties									
1	MSW L1	85	MxA-1.5	110	250	720	0.3	1.2	1.0	a
2	MSW L1	85	MxB-1.5	140	790	330	0.3	1.6	1.4	a
3	MSW L1	85	MyC-1.5	170	960$^+$	1000	0.4	2.6	2.2	a
4	Brine: pH=8.7	85	MxC-1.5	160	960	800	2.2	2.1	1.0	b
5	Brine: pH=8.7	85	MxA-1.5	91	260	720	1.4	2.5	1.2	b
6	Brine: pH=8.7	85	MyEW-1.5	180	620	4000	2.4	3	1.4	b
7	Brine: pH=8.7	85	MyE-1.5	160	1100	5200	2.3	15	7.1	b
8	Brine: pH=8.7	30	MxA-1.5	91	250	720	14	8.7	1.0	b
9	Brine: pH=8.7	30	MxC-1.5	160	960	800	21	11	1.3	b
10	Brine: pH=8.7	30	MyEW-1.5	180	620	4000	14	17	2.0	b
11	Brine: pH=8.7	30	MyE-1.5	160	1100	5200	24	55	6.3	b
	Effect of leachate									
12	MSW L3	30	MyC-1.5	170	960$^+$	1000	24	53	1.0	c
13	MSW L1	30	MyC-1.5	170	960$^+$	1000	28	59	1.1	c
14	MSW L2	30	MyC-1.5	170	960$^+$	1000	21	64	1.2	c
15	MSW L4	30	MyC-1.5	170	960$^+$	1000	27	83	1.6	c
16	MSW L5	30	MxC-1.5	170	960	800	89	-	-	d
17	ML1: pH=0.5	30	MxC-1.5	170	960	800	54	-	-	-
18	ML2: pH=1.25	30	MxC-1.5	170	960	800	48	-	-	e
19	ML3: pH=2.0	30	MxC-1.5	170	960	800	48	-	-	e
20	ML1S: pH=0.5 +surfactant	30	MxC-1.5	170	960	800	19	-	-	e
21	ML4: pH=9.5	30	MxC-1.5	170	960	800	43	-	-	f
22	ML5: pH=11.5	30	MxC-1.5	170	960	800	39	-	-	f
23	ML6: pH=13.5	30	MxC-1.5	170	960	800	25	-	-	f
24	Brine: pH=8.2	30	MxC-1.5	170	960	800	21	-	-	f
25	CL1: 0.5 ppm Cl_2 pH=9.9	30	MxC-1.5	170	960	800	10	-	-	g
26	CL2: 1 ppm Cl_2 pH= 10	30	MxC-1.5	170	960	800	8.6	-	-	g
	Effect of temperature									
27	MSW L1	60	MyC-1.5	170	960$^+$	1000	2.6	9	1.0	c
28	MSW L1	50	MyC-1.5	170	960$^+$	1000	5.5	15	1.7	c
29	MSW L1	40	MyC-1.5	170	960$^+$	1000	12	29	3.2	c
30	MSW L1	30	MyC-1.5	170	960$^+$	1000	28	59	6.6	c
31	MSW L1	60	MyA-2.0	130	380	5200	2.6	13	1.0	h
32	MSW L1	50	MyA-2.0	130	380	5200	4.0	37	2.8	h
33	MSW L1	40	MyA-2.0	130	380	5200	7.0	120	9.2	h
34	MSW L1	30	MyA-2.0	130	380	5200	12	210	30	h

Draft

	Effect of thickness									
35	MSW L2	30	MxA-1.5	140	240	1400	26	81	1.0	[i]
36	MSW L2	30	MxA-2.0	150	260	1200	29	88	1.1	[i]
37	MSW L2	30	MxA-2.5	140	240	620	32	130	1.6	[i]
38	MSW L5	30	MxC-1.5	170	960	800	89	-	-	[d]
39	MSW L5	30	MxC-2.0	170	960	950	89	-	-	[d]
40	MSW L5	30	MxC-2.4	170	960	1100	89	-	-	[d]

Std-OIT_o, HP-OIT_o , and SCR_o are value sof material when test started and may vary with length of storage (see text).

[#] Length of stage I based on Std-OIT; [*] Based on 150 hrs (50% GRI-GM13 at time);

[+]low molecular weight HALS with high mobility

[a] Abdelaal & Rowe (2015) based on 7 years of data; [b] Rowe and Shoaib (2017) 4 years data; [c] Abdelaal et al. (2014) 9 years of data; [d] Rowe and Ewais (2014c) 1 year data; [e] Rowe and Abdelaal (2016) 3 years data; [f] Abdelaal & Rowe (2017) 3 years data; [g] Abdelaal et al. (2019b) 3-7 years data; [h] Ewais et al. (2018) 17 years of data; [i] Rowe et al. (2014c) 7 years of data;

MSW L3- surfactant, trace metals, salts in RO water with Eh=-120 mV, pH~6.5 [c]
MSW L1- surfactant, trace metals, salts, volatile fatty acids in RO water with Eh=-120 mV, pH~6.5 [c]
MSW L2- surfactant, trace metals in RO water with Eh=-120 mV, pH~6.5 [c]
MSW L4- surfactant, trace metals, volatile fatty acids in RO water with Eh=-120 mV, pH~6.5 [c]
MSW L5- surfactant, trace metals mixed with tap water [c]
Brine- 200000 mg/L sodium salts (chloride, carbonate, bicarbonate) [b]
ML1-ML5 – mining solutions with different pH [e, f]

Draft

Table 9**.** Depletion adjustment factors, R_a, for geomembranes in composite liner vs immersed in leachate.

Ref	Rowe et al. (2009)	Rowe and Rimal (2008a,b)		Rowe et al. (2010, 2013)	
GMB	MyA20	MyB15		MxA15	
Thickness (mm)	2	1.5		1.5	
(1)	(2)	(3)	(4)	(5)	(6)
	Based on Eq. 5 and data from GMB immersed in leachate, water and air for ~9 years	270 g/m^2 GTX protection layer over GMB with a over GCL for ~3 years	15 mm of sand sandwiched between two 270 g/m^2 GTX protection layer, GMB, over GCL for ~3 years	580g/m^2 GTX protection layer over GMB over GCL for ~3 years	200 g/m^2 GTX over 150 mm sand over GMB over GCL for ~3 years
R_a^* ~ *24* ^{o}C	3.6	3.7	4.9	6.4	10.6
R_a at 55°C	2.9	3.3	4.4	3.1	4.7
R_a at 70°C	2.7	3.1	4.2	2.3	3.3
R_a at 85°C	2.5	2.9	4.0	1.7	2.4
Average (24-55°C)	3.3	3.5	4.7	4.8	7.7
Average (24-85°C)	2.9	3.2	4.4	3.4	5.2

* Depletion adjustment factor R_a = ratio of the depletion rate for a geomembrane immersed in leachate to that in the composite liner at a given temperature

Draft

Table 10. OIT depletion time, t_I, and time to nominal failure, t_{NF}, immersed in MSW leachate and in a composite liner in a MSW landfill (assuming negligible tensile strains in the HDPE geomembranes). Numbers rounded to 2 significant digits.

						Immersed in MSW leachate		Composite liner		
Protection (Comment)	T (°C)	GMB & thickness (mm)	Std-OIT$_o$ (min)	HP-OIT$_o$ (min)	SCR$_o$ (hrs)	t_I (yrs)	t_{NF} (yrs)	t_I (yrs)	t_{NF} (yrs)	Ref
None (Eq.5)	60	MyA-2.0	130	380	5200	2.6	13	7	54	a
	50	MyA-2.0	130	380	5200	4.0	37	12	150	a
	40	MyA-2.0	130	380	5200	7	120	23	470	a
	30	MyA-2.0	130	380	5200	12	390	40	720	a
270 g/m^2 GTX	60	MxB-1.5	140	660	>400	1.9		6.2		b
	50	MxB-1.5	140	660	>400	3.7		12		b
	40	MxB-1.5	140	660	>400	7.5		26		b
	30	MxB-1.5	140	660	>400	16		58		b
540 g/m^2 GTX + 15 mm sand	60	MxB-1.5	140	660	>400	1.9		8.3		c
	50	MxB-1.5	140	660	>400	3.7		17		c
	40	MxB-1.5	140	660	>400	7.5		35		c
	30	MxB-1.5	140	660	>400	16		76		c
580g/m^2 GTX	60	MxA-1.5	110	250	720	2.2		6		d,e,f
	50	MxA-1.5	110	250	720	4.7		15		d,e,f
	40	MxA-1.5	110	250	720	11		40		d,e,f
	30	MxA-1.5	110	250	720	26		100		d,e,f
200 g/m^2 GTX + 150 mm sand	60	MxA-1.5	110	250	720	2.2		9		d,e,f
	50	MxA-1.5	110	250	720	4.7		22		d,e,f
	40	MxA-1.5	110	250	720	11		59		d,e,f
	30	MxA-1.5	110	250	720	26		170		d,e,f
Projected R_a = 4	35	MyA-2.0	130	380	5200	9.0	210	36	840	
	35	MxB-1.5	140	660	>400	11		44		
	35	MxA-1.5	110	250	720	15		60		

[a] Ewais et al. (2018); [b] Rowe and Rimal (2008a); [c] Rowe and Rimal (2008a); [d] Rowe et al. (2010b, 2013b); [e] Rowe et al. (2013b) ; [f] Rowe et al. (2014c).

Draft