Long-term performance of leachate collections systems and geomembrane liners for MSW landfills

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ABSTRACT

This paper summarizes 12 years research into the service life of granular leachate collection systems and HDPE geomembrane liners used for municipal solid waste (MSW) landfills. It examines the effect of drainage layer particle size and filter/separator layers on leachate collection system performance and discusses service life issues. It then discusses the effects on geomembrane service life of: (a) the immersion fluid, (b) geomembrane thickness, (c) the liner configuration, (d) the protection layer above the geomembrane, (e) applied stress, (f) location in the liner system (i.e. the difference between service life for primary and secondary liners), and (g) the time-temperature history of the liner. It is shown that under many circumstances the service life of both the leachate collection system and geomembrane can be expected to be more than a century but that there are also circumstances under which the service life could be reduced to a few decades depending on design, construction and the operating conditions of the MSW landfill. It is demonstrated that HDPE geomembranes can potentially have very short or very long service lives, depending on (a) the choice of geomembrane and its consequent properties, (b) the configuration of the liner system, and (c) the time-temperature history of the geomembrane liner. This paper argues that more attention needs to be paid to these issues than has been common in the past.

1.   INTRODUCTION

Municipal solid waste (MSW) landfills typically have a barrier system comprised of a leachate collection system (LCS) and a composite liner with a geomembrane (GM) over a clay liner. The leakage of contaminants through these systems depends on (a) the leachate head on the liners and (b) the presence of holes and the composite action of the composite liner. Many of the issues associated with the migration of contaminants from modern MSW landfills have been addressed by Rowe et al. (2004). Rowe (2005) provided an assessment of the state-of-the-art with respect to the long-term performance of barrier systems. The objective of this keynote paper is to provide an update with regard to recently published research by the author's research team (predominantly since Rowe 2005 was submitted for publication) with respect to (a) the long-term performance of leachate collection systems and (b) the long-term performance of HDPE geomembrane liners used in MSW landfill liner systems.

The primary function of the leachate collection system (LCS) in a modern MSW landfill is to control the leachate head on the underlying liner, thereby minimizing contaminant leakage (advective flow) through the liner to the environment (Rowe et al. 2004). Generally this is achieved using a continuous high permeability drainage layer (e.g. gravel) in conjunction with regularly spaced pipes that lead to sumps from which the leachate is removed for treatment. The height of the leachate mound in the LCS is a function of the rate of infiltration, bottom slope, the hydraulic conductivity of the drainage layer, and pipe spacing.

Often the maximum head on the liner is stipulated, as a design criterion, not to exceed 0.3 m except for very short periods. However, it should be recognised that the 0.3m limit is largely arbitrary and the writer advocates that the maximum liner head should be selected based on a systems approach to both the design of the barrier itself (Rowe 2010) and the entire landfill (Rowe 2009). This systems

approach, which considers how to optimise the performance of the system rather just individual components of the system, seeks to minimize the long-term leakage of contaminants from the landfill. Thus, it may be acceptable to have potentially higher head than 0.3m on the liner at a limited number of locations provided that, by so doing, the actual long-term leakage was reduced. This paper will provide the technical basis for such a position without explicitly addressing the systems approach that will be dealt with elsewhere (Rowe 2009, 2010).

2.   LONG-TERM PERFORMANCE OF LEACHATE COLLECTION SYSTEMS

The leachate head on a landfill liner can be calculated using several equations including the (now discredited) Moore equations (Moore 1980, 1983; USEPA 1989), the Giroud equation (Giroud et al. 1992; Giroud and Bonaparte 2001), or the McEnroe equation (McEnroe 1989; 1993). These solutions are based on a number of simplifying assumptions, most significantly: (a) infiltration is constant and uniform, (b) flow is essentially horizontal (the Dupuit approximation), and (c) hydraulic conductivity is constant and homogeneous. While all these assumptions impose limitations on the use of the equations, the most significant is the latter since it leads to what are ultimately erroneous estimates of the leachate mound that can be expected during the period when leachate is being collected. For example, even with a flat base, leachate pipes at 50 m spacing and an infiltration rate of 0.15 m/a, the maximum head would be less than 0.3 m within the drainage layer for a sand drainage layer with a hydraulic conductivity greater than 4×10^{-5} m/s. This calculation assumes that the hydraulic conductivity of the drainage layer remains constant, however field observations (see Bass 1986; Brune et al. 1991; McBean et al. 1993; Rowe et al. 1995; Rowe 1998; Fleming et al. 1999; Craven et al. 1999; Maliva et al. 2000; Bouchez et al. 2003; Rowe et al. 2004; Rowe 2005) have concluded that the transmission of leachate through the drainage layer leads to the build-up of organic and, predominantly, inorganic clog material and a substantial reduction in hydraulic conductivity of the granular material in the drainage layer. For example, Reades *et al.* (1989) and Rowe et al. (1995, 2004) report that the top portion of a sand layer used above the liner at the Keele Valley landfill had clogged within less than 4 years and rather than providing drainage it was in fact acting as a diffusion barrier while maintaining a head on the liner.

Fleming et al. (1999) reported observations from a field exhumation of a coarse gravel (crushed dolomitic limestone of nominal 50 mm size) leachate collection layer at the Keele Valley landfill. At the time of exhumation (after about four to five years exposure to MSW leachate), the clogging of the upper unsaturated portion of the drainage layer was considerably less than that in the lower saturated zone (Figure 1). The reduction in free pore space between gravel particles (called the **void volume occupancy**, or **VVO**) was between 50-100% in the lower saturated zone of the drainage layer near the leachate collection pipe. The VVO was 30-60% in the upper unsaturated portion of the drainage layer where there was no geotextile between the waste and the gravel and 0-20% in the area where there was a geotextile. The difference in clogging of the unsaturated gravel was attributed to the woven (slit-film) geotextile preventing intrusion of waste material into the upper gravel. The biologically induced clogging in the unsaturated gravel was quite small in the four to five years of operation. While field studies such as these provide some insight, they only represent the situation at one point in time. Thus, they generally do not allow sufficient assessment of the role of various factors giving rise to the observed behaviour. Controlled laboratory tests and modelling provide means of addressing this limitation and when combined with the field observations they provide considerable opportunity for obtaining an improved understanding of the long-term performance of LCS. The exhumation reported by Fleming et al. (1999) was part of a long-term laboratory, field and modelling study initiated in 1992 and the current findings from this (still on-going) study are summarized in the following sections.

Figure 1. Partial clogging of the unsaturated and saturated coarse (50mm) gravel layer after 4-5 years as reported by Fleming et al. (1999). This system was still controlling leachate heads to below the design value.

Rowe et al. (2000a) demonstrated that mass loading arising from leachate flowing through the granular media had a significant impact on the rate and extent of clogging in a granular medium. The blockage of pores in the granular material (in this case 6 mm glass beads with an initial hydraulic conductively, k_{init}, of about 0.3 m/s) by accumulation of organic and inorganic clog material reduced the hydraulic conductivity of the porous media by 8 (or more) orders of magnitude by the time of test termination. Clogging was greatest where there was greatest mass loading. This has several practical implications. Firstly, reducing the distance between the leachate collection pipes would decrease the total volume of leachate collected for one individual pipe and hence reduce the mass loading and rate of clogging around the pipe. Secondly, other things being equal, the rate for clogging will be greatest where there is accelerated leachate generations (e.g. where there is leachate recirculation to enhance the rate of biodegradation of the waste). Even in arid regions surprisingly large amounts of leachate can be generated (Figure 2) by biodegradation of organic waste.

Figure 2. Leachate generated by biodegradation of organic waste at a MSW landfill located in a desert.

Rowe et al. (2000b) showed that particle diameter has a significant impact on the rate and extent of clogging in a granular medium. This was largely because of the increased pore size and smaller surface area per unit volume associated with larger characteristic particle size. This study supported the findings from Brune et al. (1993) that the service life of a LCS could be increased by increasing the diameter of the granular media (D_{10}) used in a leachate collection system.

Fleming and Rowe (2004) reported the initial results of a series of field-scale mesocosm experiments, which simulated the 500 mm of the drainage layer closest to the leachate collection pipe in a landfill under field conditions. These mesocosms allowed the examination of a number of variables including the effect of particle size used for the drainage media, the effect of being saturated versus unsaturated, and the effect of different filter/separator layers. McIsaac and Rowe (2007) reported the results at the termination of most of these tests after 6 to 12 years of continuous operation.

The results from the mesocosm tests supported the conclusions of Rowe et al. (2000a, 2000b) regarding the importance of loading rate and particle size as summarized above. In particular, McIsaac and Rowe (2007) reported that the 38 mm gravel performed much better over a 12.6 year period than the 19 mm gravel did over a 6 year period. A hydraulic conductivity of 5.2 x 10^{-5} m/s for the 38 mm gravel after 12.6 years was higher than the 2.7 x 10^{-5} m/s measured for the 19 mm gravel after 6 years. Less clog mass was required to cause the reduction in hydraulic conductivity for the 19 mm gravel than for the 38 mm gravel. This provided further evidence that the service life of the LCS could be extended by using relatively uniform gravel with as large a diameter particle size as possible in the granular drainage layer of a LCS.

Contrary to unsupported speculation of others that there would be dissolution of limestone by acidic leachate, there was no evidence of dissolution of the dolomitic limestone in contact with the leachate either in the laboratory mesocosms or the field (Bennett et al. 2000).

The mesocosm also provided clear evidence of very substantially increased clogging of a saturated drainage layer compared to that of an unsaturated layer due to the longer hydraulic retention time of leachate in the saturated drainage layer. In addition, McIsaac and Rowe (2007) noted that periodic increases in the leachate level into the waste layer resulted in more clogging due to siltation and the rinsing of particulate matter into the base of the drainage layer. These findings indicate that it is prudent to minimize saturation of the drainage layer by (a) incorporating a sufficient slope to the LCS; and (b) regular removal of leachate to prevent a buildup in the thickness and extent of the saturated portion of the LCS.

The mesocosm experiments were performed with leachate extracted from the LCS of the Keele Valley landfill after it had flowed through the system. The clogging observed in the mesocosm tests which were run for up to 12 years was less than that observed in the field at the Keele Valley Landfill after 4-5 years by Fleming and Rowe (1999). This suggests that the Keele Valley leachate used in the mesocosm tests had considerably lower concentrations of fatty acids and calcium than the leachate that must have been flowing into the collection system from the waste. Thus the use of the end-of-pipe leachate concentration for predicting LCS performance may not be conservative.

2.1   Modelling of clogging

To allow rational estimates of the rate of clogging of MSW LCS (and hence the service life) to be made, a numerical model (BioClog) was developed (Cooke et al. 2005a) and used to model clogging of experimental columns packed with glass beads and permeated with synthetic and real leachate (VanGulck et al. 2003) and columns packed with gravel and permeated with real leachate (Cooke et al. 2005b). Subsequently Cooke et al. (2008a) incorporated the previously developed and tested clogging processes into a 2D system for the purposes of predicting the change in the leachate mound in the LCS with time and hence to allow estimates to be made of the likely performance of different LCS designs.

The Bioclog model (Cooke et al. 2005a, 2008a) models 1D and 2D flow and transport of the critical leachate constituents through porous media using the finite element method. The key components of MSW leachate required to model biologically induced clogging of relatively uniform granular media typically used in LCS drainage layers are: microbes (suspended acetate, propionate, and butyrate degraders), dissolved organic acids (acetate, propionate, butyrate), the dissolved inorganic

constituent that predominates in clog material (calcium), and suspended particulates (inert biomass and inorganic particles). The model differentiates between active and inert biomass, and it divides the clog film that forms on a particle in the porous media into five attached films: a propionate-degrading biofilm, an acetate-degrading biofilm, a butyrate-degrading biofilm, an inert biofilm, and an inorganic solids film. A biofilm model controls growth of the substrate degrading films. Two published methods are used to predict the rate of detachment of active and inert biofilm and another two published attachment models are used to predict attachment of suspended solids. Calcium carbonate precipitation is controlled by carbonic acid production (governed by the consumption of fatty acids by the biofilm) and the availability of calcium (which limits the amount of inorganic clog material that can form). The change in porosity and specific surface of the clogged media are predicted based on the calculated film thicknesses using a geometric sphere model.

Cooke et al. (2005b) applied the Bioclog model to the transport of leachate with low suspended solids through two columns containing pea gravel. In one case the gravel consisted of particles between 2 mm and 12.7 mm (coefficient of uniformity, $Cu = 1.6$) and in the other case the pea gravel had a narrower range of particle sizes between 4.75 mm and 9.5 mm ($Cu = 1.3$). The initial hydraulic conductivity was about 1×10^{-1} m/s in both cases. The columns were operated at a flow rate selected to reflect the Darcy flux of leachate in the gravel near the drainage pipes in a LCS. The tests were terminated after about 1.3 years when the gravel became so clogged that it was not practical to maintain the desired flow. The porosity at the termination of the tests was very low (0.06-0.12) compared to the initial values (0.4-0.44) and the hydraulic conductivity had reduced by 4 to 5 orders of magnitude to between 10^{-5} and 10^{-6} m/s.

The Bioclog model successfully predicted changes in key leachate characteristics and porosity of gravel as the leachate passed through the columns. The model highlighted the facts that (Cooke et al. 2005b): (a) acetate degraders control clogging since they contribute to both a significant proportion of the biofilm and to the formation of most of the carbonate (and hence the precipitation of calcium carbonate), (b) inert biomass production is a significant process leading to large increases in organic mass, (c) the distribution of biofilm quantity and composition changes with position and time, and (d) the porosity continually decreases, but clogging is most rapid where acetate degradation is most active.

Cooke and Rowe (2008b) used BioClog to model the landfill leachate induced clogging of two full scale laboratory mesocosms (McIsaac and Rowe, 2007) performed with Keele Valley landfill leachate permeating 38 mm drainage layer gravel at realistic flow rates for 6 and 12 years. The experiments involved leachate passing both laterally through a saturated zone, and vertically through an unsaturated zone at rates that might be expected in the LCS drainage layer within 0.5 m of the perforated drainage pipe. The Bioclog model simulated the saturated zone in two dimensions and predicted the fate and transport of VFAs, suspended organic matter, and inorganic particles. A comparison of the predicated and observed porosities and film thicknesses at cell termination showed that most regions of the cell were well modelled. At the bottom of the saturated zone the observed clogging was more severe than was predicted and the model is presently being revised to address this issue.

Cooke and Rowe (2008a) illustrated the use of the Bioclog model to simulate a field case with a 0.3m thick uniform sand drainage layer sloped at 1% to collection pipes spaced 40 m apart in a saw-tooth arrangement (thus a drainage path to the nearest pipe was 20 m). Although three cases were considered in that study, only the intermediate case of a uniform "medium sand" ($d_g = 1.0$ mm) with $k_0= 1x10^{-4}$ m/s is discussed here:

For the uniform (1 mm) medium sand and other conditions (similar to what might be expect in southern Ontario, Canada), the mound shape at 2 year intervals is shown in Figure 3. In the absence of clogging the maximum leachate mound above the liner would be 0.077m (i.e. about a quarter of the drainage layer thickness of 0.3m). After an initial lag period while the biofilm on the sand particles becomes established, the leachate mound rises at a fairly constant rate for subsequent time. The typical maximum design head of 0.3m is reached after a little less than 10 years (i.e. the service life of this particular design is about 10 years). It should be noted that this is a best case scenario since the sand was assumed to be perfectly uniform. For a more well graded sand, the smaller pore size and the larger surface area that arise from having a range of particle sizes would accelerate the rate of clogging. After 10 years, porosity was predicted to have decreased from the initial 0.35 to as low as 0.25 near the collection pipe, with the average being 0.31. As might be expected, the clogging was

most extensive near the collection pipe due to the relatively large mass loading in that region. Uniform fine sand was shown to clog faster than the medium sand discussed above, and coarse (2 mm with $k_0 = 1 \times 10^{-3}$ m/s) clogged slower than the medium sand.
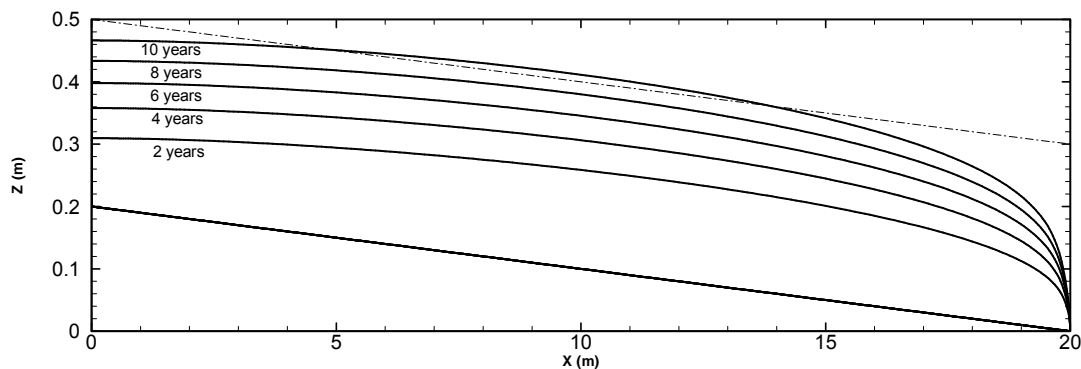

Figure 3. Modelling of clogging of a medium sand drainage layer ($k_o = 10^{-4}$ m/s). Mound surface profiles at intervals of 2 years. Reproduced from Cooke, A.J. and Rowe, R.K. (2008) 2-D Modelling of Clogging in Landfill Leachate Collection Systems, *Canadian Geotechnical Journal*, **45**(10): 1393-1409 with permission of the Canadian Geotechnical Journal.

2.2   Effect of a separator/filter layer

As noted above, in their exhumation at the Keele Valley landfill, Fleming et al. (1999) observed much greater clogging in the upper unsaturated portion of the drainage layer where there was no geotextile between the waste and the gravel than where there was a slit-film woven geotextile and attributed this to the role played by the geotextile in minimizing intrusion of waste into the coarse (500mm) gravel drainage layer. McIsaac and Rowe (2006) reported the results of a six year real time-real flow rate (i.e. not accelerated) study of the effect of different filter/separator layers placed between municipal solid waste recovered from a landfill and the 38mm gravel drainage layer in the mesocosm initiated by Fleming and Rowe (2004) on the clogging of the underlying gravel.

The McIsaac and Rowe (2006) study demonstrated, inter alia, that:

1. A filter/separator between the gravel and waste material helped reduce both the amount and rate of clogging in the underlying gravel drainage material thus maximizing the length of time the drainage material and the leachate collection pipes remain unclogged.

2. The woven geotextile between the waste and gravel was the least effective of the filter configurations examined at minimizing biochemical clogging of the underlying gravel but it did act as a good separator preventing any significant intrusion of waste into the gravel. The woven geotextile did not experience significant clogging (hydraulic conductivity only reduced by 23%).

3. The needle-punched nonwoven geotextile filter/separator experienced some biochemical clogging within the fibrous structure of the geotextile (especially at fibre intersections). This caused a reduction in hydraulic conductivity by about 90% to 4.6×10^{-5}m/s but did not cause leachate ponding during the 6 years of operation. The nonwoven geotextile minimized intrusion of waste into the gravel and also reduced the clogging of the underling gravel by both filtering out particulates and passively treating the leachate (reducing the movement of nutrients to the biofilm on the underlying gravel). The use of the nonwoven geotextile resulted in a quantifiable reduction in the void volume occupancy and mass of clog material in the saturated gravel compared to that observed with either a woven geotextile or no filter/separator was used.

4.   With a graded granular filter between the waste material and gravel, a zone of reduced permeability was focused within the sand component of the filter. The entire top layer of the sand was cemented (Figure 4) and concreted clumps of sand and pea gravel were removed from the granular filter layer (Figure 5). Of all the filters considered, the graded granular filter resulted in the least clogging of the underlying coarse gravel. This design can cause perched leachate mounding above the sand layer when it clogs. Provided that perching of leachate can be

tolerated or dealt with by other measures, the graded granular filter design would appear to provide the longest service life for the underlying drainage layer.

Figure 4. The sand layer of the granular filter system experience significant clogging. Concreted zones of cemented sand and pea gravel created a zone of reduced permeability and perched leachate mounding within the waste once the sand layer clogged. Reproduced from McIsaac, R. and Rowe, R.K. (2006) Effect of filter/separators on the clogging of leachate collection Systems, *Canadian Geotechnical Journal,* **43**(7): 674-693 with permission of the Canadian Geotechnical Journal.

Figure 5. Concreted zones of cemented sand and cemented pea gravel. Reproduced from McIsaac, R. and Rowe, R.K. (2006) Effect of filter/separators on the clogging of leachate collection Systems, *Canadian Geotechnical Journal,* **43**(7): 674-693 with permission of the Canadian Geotechnical Journal.

2.3   Unsaturated gravel

McIsaac and Rowe (2008) examined changes in leachate characteristics and drainable porosity of unsaturated columns filled with 50 mm gravel and permeated with municipal solid waste leachate over a period of up to 8 years. The gravel used was the same as that used in Stages 3 and 4 of the Keele Valley landfill (KVL). Three different thicknesses (200, 400, and 600 mm) of unsaturated gravel were examined. The following conclusions were drawn from the results of these tests.
1. Vertical percolation of leachate through the unsaturated gravel gave rise to partial treatment of leachate by the biofilm on the unsaturated gravel. The treatment in the unsaturated zone resulted in quite large reductions in the organic and inorganic concentrations in the leachate after travelling through as little as 200mm of unsaturated gravel. Thus, before leachate reaches the saturated layer of a leachate collection system, it undergoes significant treatment. This provides further evidence that the leachate collected at a municipal solid waste landfill has only a fraction of the concentration of organic contaminants (i.e. COD) and some inorganic contaminants (e.g. calcium) in the leachate entering the leachate collection system.

2. Other things being equal, a reduction in the volume of leachate generated per unit area may both reduce the amount of clogging and the concentration of organics (and hence COD) and some inorganics (e.g. Ca) in the leachate.

3. There was very little clogging within the unsaturated gravel. On average, the drainable porosity was reduced by about 8% from its original value after 8 years of operation. The biofilm only really developed on flat surfaces and at contact points between gravel particles where leachate could be retained and hence only a small fraction of the total surface area of the unsaturated gravel was covered with biofilm. The sporadic distribution of biofilm limited the biologically induced clogging of the unsaturated gravel.

4. Even though the upper 200-300 mm of unsaturated gravel experienced the greatest deposition of inorganic mass and consequent clogging, there was a benefit from increasing the gravel thickness in terms of reducing the concentration of organic and inorganic mass reaching the saturated portion of the drainage layer. This suggests that because of the significant potential to treat leachate with very little clog formation in the unsaturated gravel layer, leachate collection systems should be designed and operated such that the drainage material of the leachate collection system remains unsaturated for as long as possible. It also follows that increasing the thickness of the unsaturated gravel will increase the service life of the gravel in the drainage layer.

5. Flow in the unsaturated gravel predominantly occurred in a few free draining pathways. However, there was sufficient interaction with biofilm along these pathways to significantly decrease the concentrations of COD and calcium in the leachate reaching the bottom of the unsaturated gravel.

2.4   Use of Tire shreds in leachate collection layers

McIsaac and Rowe (2005) and Rowe and McIsaac (2005) examined different aspects of changes in leachate chemistry and drainable porosity due to clogging of coarse tire shreds being considered for use as an alternative to 38mm gravel in landfill leachate collection systems and compared the performance of the two different types of tire shred and the gravel (shown in Figure 6). This research showed that:

- At 150 kPa, the initial hydraulic conductivities of the G shred", "P shred" and the gravel drainage material (Figure 6) were about 0.007 m/s, 0.02 m/s, 0.8 m/s, respectively.
- The tire shreds were highly compressible (48% and 44% at 150 kPa) for the two types of shreds examined. Thus the unloaded thickness of the tire shreds would need to be about 600mm to achieve a final drainage layer thickness of 300 mm even for a relatively low 150 kPa final overburden pressure.
- Unlike large relatively uniform void sizes and generally an open void structure of gravel, the pore structure of the tire shreds had numerous narrow and constricted or confined pathways and voids that connected relatively isolated larger pores.
- In a given period of time (other things being essentially equal), much more precipitation of hard inorganic calcium clog material was observed for the tire shreds than for the gravel.
- The drop in hydraulic conductivity due to clogging is mostly affected by the critical opening sizes (which were substantially smaller for the tire shreds than for the gravel) rather than the total void space available to be clogged.
- More clog formation was required to bridge over the larger distances between particles and larger volumes in the gravel than that for the narrow constrictions and smaller pore throats in the shred material. Thus, due to the lower initial porosity and the more complex pore structure of the tire shreds relative to gravel, the tire shreds clogged substantially (3 times) faster than the gravel.
- The empirical data suggested that for the tire shreds examined, an initial (uncompressed) tire shred thickness of about 0.9 m would be required for an overburden stress of 150 kPa to get a similar service life with respect to clogging as 0.3 m of gravel. For higher vertical stresses, even thicker rubber tire shred layers would be required to provide equivalent performance as gravel.
- Due to the highly compressible nature of tire shreds, the use of tire shreds for pipe bedding is highly questionable since they will not provide the lateral support usually relied upon in the design of these systems (Rowe et al. 2004).
- The permeation of leachate through tire shreds leached elements such as Al, Cu, Zn, and Fe from the shreds (especially those with significant amounts of exposed wire) although, in these tests, the metals became incorporated in the clog material and were not detected at elevated levels in the effluent leachate.

It was concluded that considerable care is required in developing designs to replace gravel with tire shred. Gravel should be used in critical zones where there is a high mass loading (e.g. near leachate collection pipes or leachate sumps). Tire shreds could be used in less critical zones (e.g. side slopes) although, even then, an increased thickness of compressed tire shred will be required to give a service life similar to that of a given thickness of gravel.

Figure 6. Tire shred and 38mm gravel considered by McIsaac and Rowe (2005) and Rowe and McIsssac (2005)

3. TEMPERATURE ON LINERS

As will be demonstrated in the following section, the temperature of an HDPE geomembrane liner is probably the most significant factor affecting its service life and hence long-term performance. Rowe (2005) provided an initial compilation of published data and this has been updated by Rowe and Islam (2009). This data is helpful for giving an idea of peak liner temperatures but, unfortunately, there is insufficient data to fully define the time-temperature history for modern landfills and more liner long-term temperature monitoring is required. The rate of increase in liner temperature with time and, to some extent, the final liner temperature can depend on factors such as (Rowe and Islam, 2009) (a) landfill location and local climate, (b) the amount and nature of organic waste and inorganic waste such as fly-ash, (c) the rate of waste filling, (d) the waste temperature at the time of placement, (e) availability of moisture to encourage biodegradation of organic matter (or hydration of fly-ash) and, in particular, operational factors such as leachate recirculation and moisture addition.

Based on the available data (Rowe and Islam, 2009), it appears that for MSW landfills the temperature increases to a maximum value within about 4-16 years of the commencement of landfilling at a given location and stays at peak temperature for a period of time. It then starts to decrease (although in no case is there sufficient time history of data to show a return to the original temperatures as may be expected eventually). The peak liner temperature is most commonly in the 30-40°C range although temperatures in the 50-60°C range can also be encountered when there is ample moisture to accelerate biodegradation of the organic matter in the waste. Although not documented in the public literature, there is anecdotal evidence that much higher temperatures have been observed in some landfills, although it is suspected that this may be related to disposal of waste other than traditional MSW.

4. LONG-TERM PERFOMANCE OF HDPE GEOMEMBRANE LINERS

4.1 Factors affecting HDPE geomembrane service life

The service life of high density polyethylene (HDPE) geomembranes used in geoenvironmental applications may be considered to be the length of time the geomembrane acts as an effective hydraulic and diffusive barrier to contaminant migration (Rowe et al. 2004). Any geomembrane is expected to experience some ageing or degradation during its service life. Typical modes of degradation include oxidation, extraction, biological degradation, ultraviolet (UV) degradation, and thermal degradation. Of these, oxidative degradation is the primary concern for HDPE

geomembranes used as bottom liners in MSW landfills (Hsuan and Koerner 1995; Sangam and Rowe 2002b). Oxidation in the polymer increases exponentially with temperature (Hsuan and Koerner 1995; Sangam and Rowe 2002a). Oxidative degradation causes a breakdown in polymer chains, which changes the physical and mechanical properties of the geomembrane and eventually leads to geomembrane embrittlement and failure. The most likely cause of failure is considered to be environmental stress cracking of the geomembrane at locations of elevated stress, once the stress crack resistance has dropped sufficiently.

Modern HDPE geomembranes are manufactured from a medium density polyethylene (MDPE) resin to which 2-3% carbon black is added for UV stabilization and it is the carbon black that pushes the geomembrane into the high density classification. Earlier geomembranes were manufactured from true HDPE resin but problems were encountered with these older geomembranes due to inadequate environmental stress crack resistance. There are a number of different resins used by geomembrane manufacturers and these resins may have quite different properties. For example, Scheirs (2009) reports that the two most widely used HDPE geomembrane resin grades (Marlex K306 and K307 from Chevron Phillips) have very different molecular weights due to that fact that they are produced for two different methods of geomembrane production with K306 being used for geomembrane produced using round dies (blown film method) and K307 for geomembrane produced using flat dies (cast extrusion method). Many other resins are available and are used by manufacturers. Even for a given manufacturer the resin used in the geomembrane can vary from time to time. The properties of the geomembrane such as the environmental stress crack resistance (SCR) can vary substantially depending on the resin used and illustrated in Table 1 for geomembranes produced by two different manufacturers (A and B at different times denoted by a,b,c).

Table 1. Some characteristics of geomembranes discussed in this paper

Geomembrane Type	Manufacturer	Thickness (mm)	Std-OIT (min)	HP-OIT (min)	Stress Crack Resistance (hours)
GM1	Aa	2	133	380	5220
GM2	Ab	1.5	135	660	3740
GM5	Ac	1.5	174	900	1000
GM7	Ba	1.5	135	245	1430
GM8	Ba	2	150	265	1250
GM9	Ba	2.5	136	235	620
GM10 -13	Bc	1.0, 1.5, 2.0, 2.4	173	970	>400
GM14	Bb	1.5	172	790	500

Typically at least one primary and one secondary antioxidant is added to the HDPE resin to delay or retard the oxidation reactions both during and following manufacture of the geomembrane. Antioxidants may represent 0.2-0.5% of the geomembrane by weight (Grassie and Scott 1995). The primary and secondary antioxidants most commonly used in HDPE geomembranes, are hindered phenols and phosphites, respectively (Thilén and Shishoo 2000; Marcato et al. 2003; Garcia et al. 2004). A third group of antioxidants that are used are hindered amine light stabilizers (HALS).

Antioxidants react with free radicals and hydroperoxides that are generated due to oxidation and convert them into stable molecules (Grassie and Scott 1995). Antioxidants in the geomembrane are depleted due to their chemical reactions with oxygenated free radicals and hydroperoxide and/or physical loss by diffusion, evaporation or extraction (Sangam and Rowe 2002b; Garcia et al. 2004). The potential for migration of phosphitic antioxidants is greater than that of phenolic antioxidants (Marcato et al. 2003), however no optimum combination of type and concentration of antioxidants is apparent from the literature (Gugumus 1998a, b). Antioxidant packages may change from supplier to supplier and for a given supplier from time to time (Table 1) and hence the service life of one geomembrane will likely not be the same as that for another geomembrane under the same exposure conditions unless the geomembranes has both the same resin and antioxidant package. Even with one given manufacturer the geomembrane produced from time to time may be expected to have a difference in service life due to differences in the resin and antioxidant package used. This should be

kept in mind when considering the service lives discussed in this paper – each was deduced for a particular geomembrane and may not be relevant to other geomembranes with different properties.

The oxidative degradation of HDPE geomembranes is considered as a three-stage process (Viebke et al. 1994; Hsuan and Koerner 1998): the depletion of antioxidants (Stage 1), induction time to onset of polymer degradation (Stage 2), and degradation to failure (Stage 3). The service life of a geomembrane is taken as the sum of the duration of the three stages. Stage III is characterized by significant changes to the physical and mechanical properties, which will eventually lead to geomembrane failure. Failure in this context refers to a decrease in an engineering property (e.g. stress crack resistance, tensile break stress, tensile break strain) to a specified value. Since the most likely mechanism for failure is cracking of the geomembrane at locations of elevated tensile stress, the writer considers stress crack resistance to be the most important physical characteristics. The value defining the end of Stage III is somewhat subjective and engineers may select different definitions depending on circumstances. The two most commonly used approaches correspond to 50% of the initial property (Hsuan and Koerner 1998) or 50% of the specified property value (Rowe et al. 2009). The latter approach is fairer for products whose initial value of a property significantly exceeds the minimum specified value (e.g. stress crack resistance >300 hours as specified by GRI, 1997).

Laboratory based accelerated ageing tests are utilized to estimate the length of these stages with the emphasis to date being on Stage I (Hsuan and Koerner, 1998; Sangam and Rowe, 2002a; Müller and Jacob, 2003; and Gulec *et al.* 2004). These previous studies have examined extraction of antioxidants from geomembrane immersed in air, water, leachate and various hydrocarbons. As discussed in the following sections, the service life of the geomembrane will depend on a number of factors such as: (a) the immersion fluid, (b) geomembrane thickness, (c) the liner configuration, (d) the protection layer above the geomembrane, (e) applied stress, (f) location in the liner system (i.e. the difference between service life for primary and secondary liners), and (g) the time-temperature history of the liner.

4.2   Effect of immersion fluid of antioxidant depletion

Sangam and Rowe (2002a) examined the performance of a 2mm thick geomembrane (GM1, Table 1) and demonstrated that the time to the end of Stage 1 of the geomembrane service life (antioxidant depletion) varies substantially depending on the immersion medium, with the depletion in a simulated MSW leachate being substantially shorter than for the same geomembrane in water. However it was not clear from this study what constituent(s) in the leachate was/were responsible for this relatively rapid depletion of antioxidants. Rowe et al. (2008) examined this question.

Table 2. Estimated time for antioxidant depletion for GM1 immersed in different fluids at different temperatures (adapted from Sangam and Rowe 2002a). Estimates rounded to nearest 5 years.

Temperature (°C)	Antioxidant Depletion Time (years)			
	Air	Water	Leachate	Leachate-Unsat. Soil
20	190	95	25	85
35	65	35	10	30
50	25	15	5	10

Rowe et al. (2008) studied ageing of 1.5mm thick HDPE geomembrane (GM5 in Table 1) immersed in four different synthetic leachates as indicated in Table 3. It was found that the presence or absence of the volatile fatty acids and the typical primary inorganic constituents (Cl, Na, Ca, Mg, etc.) had negligible effect on the depletion of antioxidants and there was only a small difference between the activation energies (62.5 and 64.0kJ/mol) obtained for the four leachates. The constituent of leachate responsible for the significant difference in antioxidant depletion rate between geomembranes immersed in water and synthetic leachate was surfactant (e.g. soap). As the surfactant concentration increased to about 1 mL/L the majority of the effect was evident. There was no further increase in depletion rate for any increase in surfactant concentration beyond 5mL/L.

Rowe et al. (2008) also examined antioxidant depletion as a function of pH of the fluid in which the geomembrane was immersed. They demonstrated that antioxidants were depleted at a faster rate in relatively acidic or basic immersion mediums (pH 4 and 10) than when in contact with typical MSW leachate (pHs 6-8). This suggested that the service lives for geomembranes in contact with MSW leachate may be different to that of geomembranes used for hazardous waste, where the pH can be high, or in heap leach pads where the pH can be very low. Research into these cases is in progress.

Table 3. Four synthetic leachate examined by Rowe et al. (2008)

Component	Leachate Type			
	L1	L2	L3	L4
Fatty Acids (FA)	√	x	x	√
Inorganics (IO)	√	x	√	x
Trace Metals (TM)	√	√	√	√
Surfactant (S)	√	√	√	√

4.3   Effect of geomembrane thickness

The minimum HDPE geomembrane thickness permitted in developed countries typically ranges from 1.5 mm to 2.5 mm. For example, Ontario (Canada) requires a minimum 1.5 mm thick geomembrane for the primary landfill liner and a 2.0 mm thick geomembrane for any secondary landfill liner because of the expected longer required service life of a secondary geomembrane liner. Thus it is generally expected that a thicker geomembrane will have greater strength, higher puncture resistance, greater resistance to chemicals, and a longer service life.

Rowe et al. (2009) examined the depletion of antioxidants from three commercially available HDPE geomembranes having nominal thicknesses of 1.5, 2.0, and 2.5 mm (GM7, GM8 and GM9 in Table 1). Table 4 summarizes the projected length of Stage 1 at three different temperatures for these three geomembranes. The results show that the thickness of the geomembrane had a significant effect on the depletion of antioxidants with the thicker (2.5 mm) geomembrane giving the longest antioxidant depletion time (by about 50% at all temperatures examined). The results of melt index (MI) and stress crack resistance also indicate that a thinner geomembrane is more susceptible to degradation than a thicker geomembrane. Thus, other things being equal, a thicker geomembrane is likely to have a longer service life than the thinner geomembrane and may be more appropriate when the 1.5 mm geomembrane can not provide adequate service life. This finding validates the choice of a thicker geomembrane for secondary liners required to have a longer service life than primary liners as indicated in some regulations (e.g. MoE 1998). However it should be remembered that the resin and the antioxidant package used will also have a significant effect on the service life of the geomembrane.

Table 4. Estimated times for antioxidant depletion for GM7, 8 and 9 immersed in simulated MSW leachate (adapted from Rowe et al. 2009).

Temperature (^{o}C)	Antioxidant Depletion Time (years)		
	1.5mm	2.0mm	2.5mm
20	45	57	66
35	13	17	20
50	4.4	5.7	6.7

4.4   Effect of position in a composite liner compared to immersion on antioxidant depletion

Most testing conducted to assess the rate of antioxidant depletion has been on geomembranes immersed in fluid as described above. Hsuan and Koerner (1998) also examined a case with water saturated sand above and dry sand below the geomembrane. However, until the recent work of Rowe and Rimal (2008a), there had been no examination of antioxidant depletion rate for a

geomembrane in a simulated composite liner environment nor any comparison of this with that obtained from more conventional immersion tests.

Rowe and Rimal (2008a), reported results of accelerated ageing tests conducted for a 1.5mm thick geomembrane (GM2, Table 1) both (a) immersed in simulated MSW leachate, and (b) in a composite liner where there was a gravel layer (with leachate) a geotextile protection layer, the geomembrane, a hydrated GCL and underlying sand foundation layer. The results from antioxidant depletion monitoring indicated that the antioxidant depletion rates were about 2.2-4.8 times faster for the leachate immersed geomembrane than the geomembrane in the simulated composite liner. The higher rates of antioxidant depletion for the immersed geomembrane were attributed to the fact that the antioxidants could be readily leached from two sides of the geomembrane. In contrast, for the geomembrane in the composite liner there was potential for a build-up of antioxidants on the bottom interface of geomembrane, which slowed the antioxidant depletion processes.

The measured antioxidant depletion rates were extrapolated to a range of temperatures (Table 5) using Arrhenius modelling and depletion times for the consumption of antioxidant were estimated. The results (Table 5) indicate that at a liner temperature of $35^{o}C$ the antioxidant depletion time would be 40 years for the composite liner geomembrane compared to 10 years for the geomembrane immersed leachate. This work demonstrated that to obtain a realistic estimate of a geomembrane's service life one needs to perform tests, which simulate the expected conditions in a composite liner.

Table 5. Estimated times for antioxidant depletion for GM2 immersed in simulated MSW leachate and in three different composite liner configurations (adapted from Rowe and Rimal 2008a,b).

Ageing Condition	Antioxidant Depletion Time (years)		
	$20^{o}C$	$35^{o}C$	$50^{o}C$
Leachate immersed	35	10	4
Composite liner with GT protection layer	135	40	10
Composite liner with 1.5 cm sand protection layer	180	50	15
Composite liner with GCL protection layer	230	65	20

Rowe and Rimal (2008b) extended this work by conducting experiments to examine the depletion of antioxidant from a geomembrane separated from the gravel containing leachate by: (1) a traditional nonwoven geotextile (as discussed above), (2) a geotextile and GCL, and (3) a geotextile-1.5cm sand-geotextile layer. The GCL protection layer gave an antioxidant depletion rate 0.59 to 0.66 times slower than the traditional geotextile layer alone. The 1.5 cm sand protection layer gave depletion rates 0.72-0.75 times that of the traditional geotextile. Based on Arrhenius modelling, the time required for depletion of antioxidants at $35^{o}C$ (Table 5) increased from 40 years for a geomembrane with a traditional geotextile protection layer, to 50 years for a 1.5cm-sand protection layer and 65 years the GCL protection layer. These times were all significantly greater than the depletion time for geomembrane immersed in leachate (10 years) for the geomembrane tested.

4.5   Modelling diffusion of antioxidants from the geomembrane

Rimal and Rowe (2009) reported the results of a study which modelled the diffusion of antioxidants from geomembrane GM2 (Table 1) which was stabilized using hindered phenols and phosphites (no HALS were identified) for the tests described by Rowe and Rimal (2008a,b). It was shown that predictions of antioxidant depletion time based on a first-order approximation to short-term antioxidant depletion data (i.e. where there is still significant antioxidant remaining when the last data was collected) were conservative compared to predicted depletion time based on the diffusion modelling.

Diffusion parameters were deduced for the antioxidants used in this geomembrane and based on these parameters good predictions could be made of the depletion rates for other more complex tests. These parameters were used to predict antioxidant depletion with different types of protection layers over the geomembrane and, in particular, a 30 cm thick sand protection layer. At a liner temperature

of 35°C the antioxidant depletion time was predicted to be about 100 years longer for the 30cm sand protection layer than for the case with the 1.5 cm sand layer.

4.6   Test conducted using geosynthetic landfill liner simulators (GLLS)

Brachman et al. (2008) described the development of a new experimental apparatus that is capable of simulating the ageing of geomembranes under the combined effects of chemical exposure, elevated temperatures and applied stresses up to 1000 kPa. Figure 7 shows a cross-section through the new laboratory apparatus–called a Geosynthetic Landfill Liner Simulator (GLLS). The GLLS is a cylindrical stainless steel pressure vessel with an internal diameter of 600 mm and height of 470 mm. Fifty GLLS were constructed to allow long-term testing that considers a range of temperature and liner variables.

The GLLS allows construction of a full liner system: foundation layer (e.g. SP sand; GCL, geomembrane, protection layer (e.g. geotextile GT), and gravel (GP) drainage layer inside the cell. Pressure is applied, leachate is circulated through the gravel drainage layer, and the cell heated to the desired temperature. The cell is surrounded by an insulation layer (Figure 8) to minimize heat loss and aid in controlling the temperature to within 1°C of the target temperature (typically 35, 55, 70 or 85°C). A special side wall friction treatment system is used to ensure that at least 95% of the applied stress is transferred to the liner system (Figure 9).

To assess what (if any) effect applied stress may have on antioxidant depletions, accelerated ageing tests were conducted under a 250 kPa vertical pressure in the GLLS at 55, 70, and 85°C as described by Rowe et al. (2009). The simulated landfill liner consisted of (from the top down) a 150 mm thick gravel layer, a geotextile protection layer, a 1.5mm geomembrane GM7 (Table 1), a GCL, and a 150 mm thick sand foundation layer.

It was found that the antioxidant depletion rate in the GLLS was consistently lower than for more traditional leachate immersion tests for the same geomembrane and that the predictions of the time to antioxidant depletion (Table 6) were about 4 times longer for the geomembrane in the GLLSs than for the same geomembrane immersed in simulated MSW leachate. No statistically significant difference was observed in the depletion of antioxidant from geomembrane located between points of contact with the overlying gravel and those directly beneath the gravel – possible because the geotextile provided a conduit for leachate to reach the geomembrane.
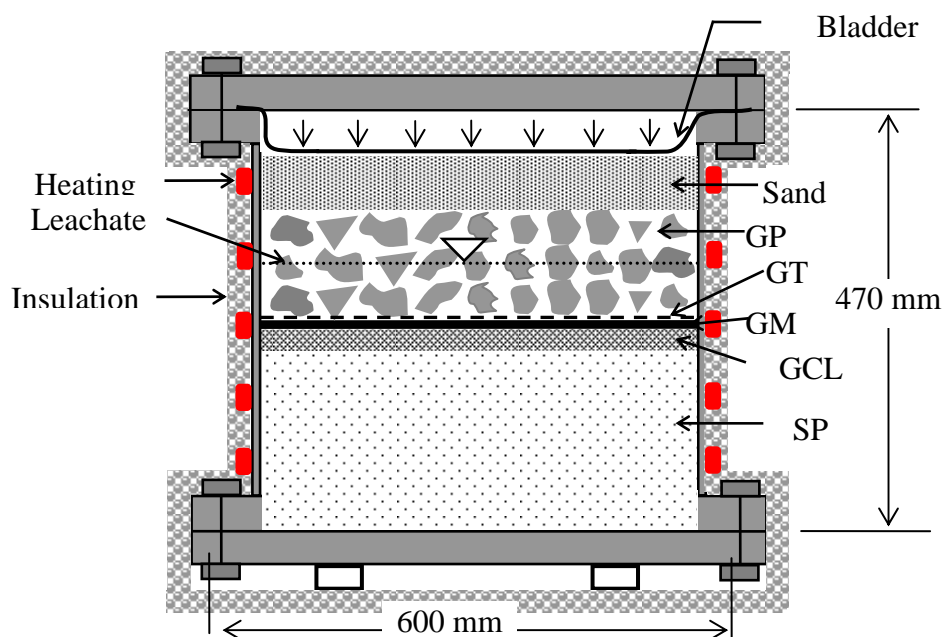

Figure 7. Cross-section through GLLS (Brachman et al. 2008)

Figure 8. Photograph of six GLLSs tests in progress and an additional one (lower left) being assembled.

Table 6. Estimated times for antioxidant depletion for GM7 immersed in simulated MSW leachate and in the GLLS with a geotextile protection layer at 250 kPa (adapted from Rowe et al. 2009b).Times above 10 years rounded to nearest 5 years.

Ageing condition	Antioxidant Depletion Time (years)	
	35°C	50°C
Leachate immersed	15	4
Composite liner with GT protection layer at 250kPa	65	15
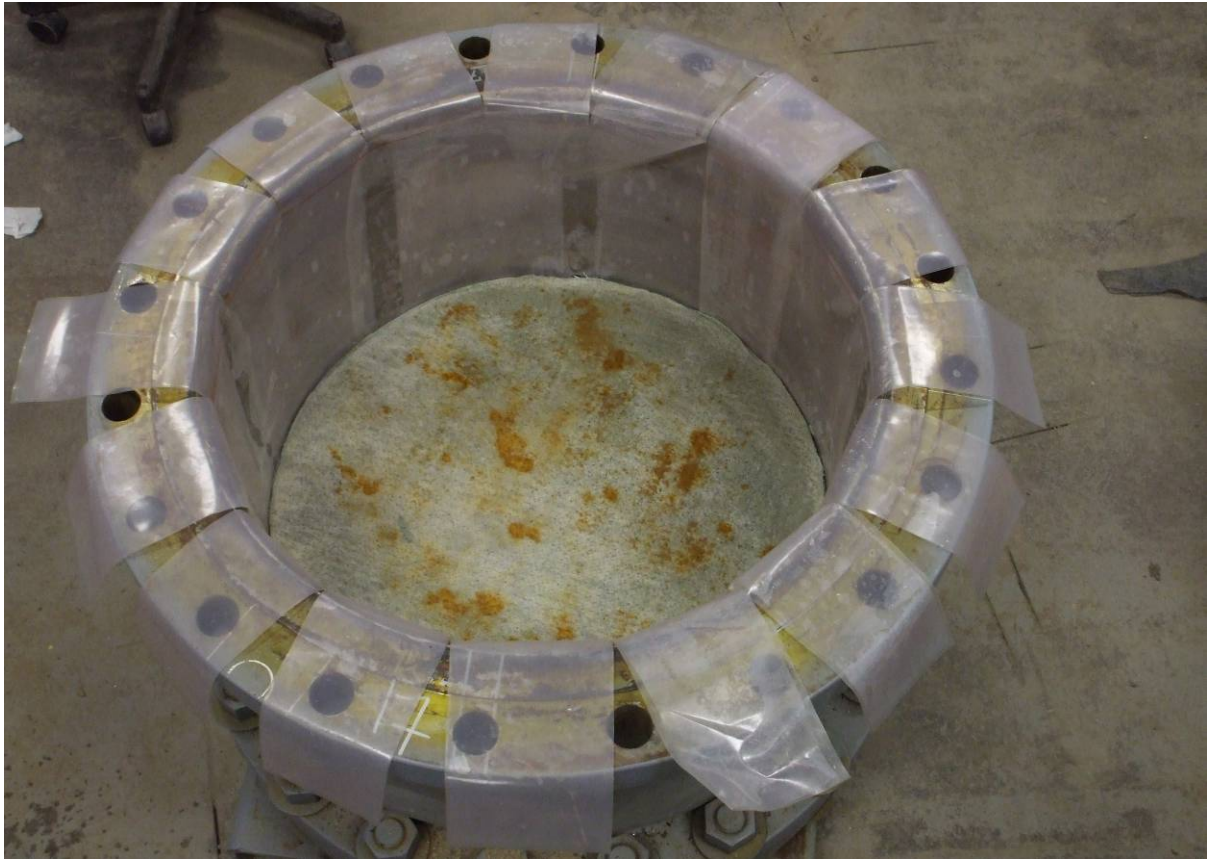
Figure 9. GLLS being assembled. A special friction treatment is used to ensure that 95% (or more) of the applied stress is transferred to the liner system (see Brachman et al. 2008 for details).

4.7   Predication of geomembrane service life

Most published data concerning the ageing of geomembranes (including that above) tends to focus on Stage 1 (antioxidant depletion) of the geomembrane service life. The reason for this is that even at elevated temperatures it takes a very considerable period of time (generally more than a decade at temperatures of 70°C or below) to go through Stages I, II and II in sequence. Rowe et al. (2009c) reported the initial results of a decade long study of the ageing of 2 mm thick GM1 (Table 1) immersed in air, water and simulated MSW landfill leachate. For the geomembrane and conditions examined, and based on the currently available data, it was concluded that:

1. At 85°C geomembrane GM1 passed from Stage II into Stage III, with an observed decrease in MFI with time attributed to the oxidative cross-linking. There was a corresponding decrease in SCR and tensile properties at break. The SCR was more critical than tensile properties in terms of estimating the geomembrane service life (giving shorter service lives). The service life at 85°C for the geomembrane was greatest in air and least in leachate (8.7 years in air, 5.3 years in water, 3.4 years immersed in leachate based on SCR). Based on the averaging technique used by Sangam and Rowe (2002a) the estimated service life of the geomembrane in a composite liner at 85°C would therefore be about 5 years.

2. The service life of GM1 immersed in leachate is likely to exceed 700 years at 20°C, more than 150 years and likely 225-375 years at 35°C and more than 40 years and likely 50-90 years at 50°C. However these are preliminary estimates and may change as more data becomes available over the next five years. The service life in a liner configuration may be expected to be longer than when immersed in leachate.

3. Predictions of service life of the geomembrane were made for the end of Stage I based on a residual oxidative induction time $OIT_{(f)}$=0.5 min for resin without carbon black and also using $OIT_{(f)}$=1min which is more typical of a geomembrane with carbon black. The uncertainty regarding $OIT_{(f)}$ had no significant influence on the predicted service lives.

4.8   Secondary geomembrane service life

Previous studies (e.g. Rowe 2005) have predicted the service life of geomembranes forming part of the primary liner (PGM). However until the recent work of Rowe and Hoor (2009) no one had examined the likely temperature of the secondary geomembrane (SGM). Modelling of heat transfer from the primary to secondary geomembrane liner for different double liner systems indicated that for the typical liner materials studied, the steady state temperature profile was not very sensitive to thermal properties of liner materials but was highly dependant on the thickness of the soil component of the primary liner.

The service life of the secondary geomembrane liner was a minimum for an all-geosynthetic system and increased with increasing thickness of the primary liner (Table 7). This study highlighted the need to consider the temperature of the secondary geomembrane liner in the design of MSW landfills to ensure that the service life of the system is likely to exceed the contaminating lifespan for a particular design.

Table 7. Estimated increase in the service life of a secondary geomembrane compared to an otherwise similar primary geomembrane (adapted from Rowe and Hoor, 2009).

Temperature of Primary geomembrane (PGM) (^{o}C)	Increase in Service Life of SGM Compared to PGM (years)	
	All Geosynthetic Liner System	1m thick Primarily Liner
30	40	120
40	20	65
50	5	30

4.9   Time-temperature history and its effect on geomembrane service life

Rowe and Islam (2009) examined the available time-temperature history for landfill liners. Based on this information and data as discussed above relating to geomembranes GM1, GM2, GM5, GM6, GM7 and GM8, they made predications of both the antioxidant depletion time and the possible service life of the geomembranes for different hypothetical time-temperature histories. It was assumed that the temperature at the base of the landfill started at a typical ground temperature (in the absence of landfilling) of T_o and remained constant until a time t_1 (which may in some cases be zero). The temperature then increased linearly to a peak value of T_p at time t_2 and remained constant until a time t_3. After time t_3, the temperature decreased linearly and reached the initial temperature T_o at time t_4 and remained constant thereafter (Figure 10).
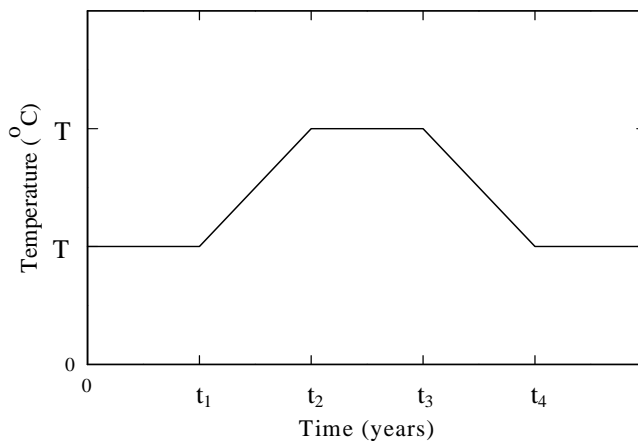

Figure 10. Idealized temperature variation with time in a landfill.

This study demonstrated that the service life was extremely sensitive to the time-temperature history with service lives ranging between thousands of years and a few decades (Table 8). This range illustrates the important role that time-temperature history could play in terms of geomembrane service life and highlights the need for long-term monitoring of landfill liner temperature. It also demonstrated the significant potential effect of even a relatively short period of time at elevated temperatures above 50°C.

Table 8. Estimated geomembrane service lives for two different hypothetical time-temperature histories (adapted form Rowe and Islam, 2009)

t_1 (years)	t_2 (years)	t_3 (years)	t_4 (years)	T_o (^{o}C)	T_p (^{o}C)	Service Life (years)
8	14	20	40	10	37	1900-3300
0	8	30	40	20	60	20-30

5. CONCLUSIONS

Research into the long-term performance of leachate collection systems has highlighted a number of important considerations for use in the design of leachate collection systems (LCS) for modern MSW landfills as summarized below.

- Leachate that has the potential to cause clogging of leachate collection systems can be generated even in arid climates if there is a significant amount of organic waste.
- The leachate that is collected from modern landfills does not represent the leachate that enters the system. The biological processes that give rise to clogging of LCS also serve to reduce the concentration of both organic acids (and hence COD, BOD) and inorganic contaminants that are susceptible to precipitation (e.g. calcium and some heavy metals). Thus, any predictions of the service life of LCS must be performed using estimates of the leachate characteristics of the leachate **entering** the LCS and **should not be based on the characteristics of the effluent from existing LCS**.
- Laboratory studies of clogging must use a leachate as representative as possible of that likely to be entering the system being examined. Generally this will not be the same as the leachate collected after it has passed through a modern LCS. The tests must also be run long enough to obtain realistic results; this likely means years even for accelerated tests except for tests on finer material (which clogs very quickly).
- A sand layer provides a good protection layer for the underlying liner and in so doing can perform a valuable function in this capacity. However it should not be relied upon as a drainage layer for MSW leachate due to its high potential for clogging. An optimal system is likely to involve a sand protection layer above the liner and a gravel leachate drainage layer above the sand.
- The coarser and more uniform the gravel, the longer will be its service life as a leachate drainage layer in a MSW landfill.
- Drainage layers are more prone to clog when kept saturated; thus it is recommended that leachate should not be allowed to back-up in the leachate collection system since this would: (a) accelerate clogging of the LCS and (b) impose a head on the liner that will increase leakage through any holes in the liner.
- The unsaturated gravel can perform a useful function in treating leachate (e.g. reducing the concentrations of organic acids and calcium) before it reaches the saturated portion of the drainage layer. Other things being equal, the thicker the unsaturated portion of the drainage layer the greater the amount of leachate treatment and the longer the service life of the LCS.
- Clogging is related to the mass loading and is likely to be greatest near sumps and drainage pipes where the leachate flow is greatest. Clogging is also likely to be increased (other things being equal) when leachate is recirculated.
- When there is a continuous drainage layer, the placement of a suitable filter/separator layer between the waste and the underlying granular drainage layer will extend the service life of the LCS by (a) minimizing waste intrusion, (b) minimizing the migration of fines and other particulates

into the drainage layer, and (c) providing some leachate treatment (reduction in organic acids and cations such as calcium) before it enters the drainage layer. In performing this role, the filter/separator layer will experience some clogging and a reduction of hydraulic conductivity (values of the order $3x10^{-8}$ m/s have been observed). However, one can design to deal with the level of perched leachate provided that there is a drainage layer below the filter and hence the head does not act on the liner and can not escape to the environment.

- Considerable care is required in developing designs to replace gravel with tire shred. Gravel should be used in critical zones where there is a high mass loading (e.g. near leachate collection pipes or leachate sumps). Tire shreds could be used in less critical zones (e.g. side slopes) although, even then, an increased thickness of compressed tire shred will be needed to give a service life similar to that of a given thickness of gravel.

- Although there has been inadequate research regarding the effects of co-disposal of incinerator ash and MSW, the writer has been contacted in a number of cases by operators who are having problems with clogging of their LCS in situations where there has been co-disposal of incinerator ash (with high calcium, Ca^{2+}) and MSW (where the biodegradation of organic waste provides the CO_3^{2-}). More research is required on this topic; however, considerable caution should be exercised in the design of LCS for landfills where there will be co-disposal of incinerator ash and MSW.

Based on the available data, it appears that for MSW landfills the temperature increases to a maximum value within about 4-16 years of the commencement of landfilling at a given location and stays at peak temperature for a period of time. It then starts to decrease (although in no case is there sufficient time history of data to show a return to the original temperatures as may be expected eventually). The peak liner temperature is most commonly in the 30-40°C range although temperatures in the 50-60°C range can also be encountered when there is ample moisture to accelerate biodegradation of the organic matter in the waste. There is anecdotal evidence that even higher temperatures may sometimes be expected.

Resent research into the long-term performance of geomembrane liners has indicated that:

- The service life of one geomembrane will likely not be the same as that for another geomembrane under the same exposure conditions unless the geomembranes have both the same resin and antioxidant package. Since the antioxidant packages and resins used by geomembrane manufactures change from time to time, the geomembrane service lives can be expected to change from manufacturer to manufacture and even from time to time with the same manufacturer.

- The presence or absence of the volatile fatty acids and the typical primary inorganic constituent had negligible effect of the depletion of antioxidants for geomembranes immersed in synthetic MSW leachate. The constituent of leachate responsible for the significant difference in antioxidant depletion rate between geomembranes immersed in water and synthetic leachate was surfactant (e.g. soap).

- Antioxidants were depleted at a faster rate in relatively acidic or basic immersion mediums (pH 4 and 10) than at typical MSW leachate (pHs 6-8). This suggested that the service lives for geomembranes in contact with MSW leachate may be different to that of geomembranes used for hazardous waste, where the pH can be high, or in heap leach pads where the pH can be very low.

- Other things being similar, a thicker geomembrane is likely to have a longer service life than the thinner geomembrane. Thus a thicker geomembrane may be appropriate when the 1.5 mm geomembrane can not provide adequate service life.

- Antioxidant depletion was about 2.2-4.8 times faster for a geomembrane immersed in leachate than the same geomembrane in a simulated composite liner. Thus to obtain realistic estimate of geomembrane service life one needs to perform test which simulate the expected conditions in a composite liner.

- Based on modelling of the diffusion of antioxidants, the antioxidant depletion time for a liner temperature of 35°C was predicted to be about 100 years (or more) longer for a 30 cm sand protection layer than for the traditional case with just a geotextile protection layer or a thin (1.5 cm) sand protection layer.

- Tests conducted in new experimental apparatus that simulated the ageing of geomembranes under the combined effects of chemical exposure from synthetic MSW leachate and an applied stress of 250 kPa at elevated temperatures, gave antioxidant depletion times about four times longer than for the same geomembrane immersed in leachate.

- For a geomembrane incubated at 85°C there was an observed decrease in melt index with time attributed to the oxidative cross-linking even though the geomembrane was immersed in a highly reduced leachate. There was a corresponding decrease in stress crack resistance (SCR) and tensile properties at break. The SCR was more critical than tensile properties in terms of estimating the geomembrane service life (i.e. it gave shorter service lives). The service life at 85°C for the geomembrane was greatest when it was immersed in air and least when immersed in leachate (8.7 years in air, 5.3 years in water, 3.4 years in leachate based on SCR). Based on the averaging technique used by Sangam and Rowe (2002a) the estimated service life of the geomembrane in a composite liner at 85°C would therefore be about 5 years.
- Based on the available data it was estimated that the service life of the geomembrane tested (immersed in leachate) is likely to exceed 700 years at 20°C, more than 150 years (and likely 225-375 years) at 35°C and more than 40 years (and likely 50-90 years) at 50°C. However these are preliminary estimates and may change as more data becomes available over the next five years.
- Modelling of heat transfer from the primary to secondary geomembrane liner for different double liner systems, it was found that the steady state temperature profile was not very sensitive to thermal properties of liner materials but was highly dependant on the thickness of the soil component of the primary liner.
- For the geomembrane considered, the increase in the service life of the secondary geomembrane compared to an otherwise similar primary geomembrane liner was a minimum of 40, 20 and 5 years at 30, 40 and 50°C respectively for an all-geosynthetic system and increased with increasing thickness of the primary liner to 120, 65 and 30 years at 30, 40 and 50°C respectively for a 1 m thick primary liner.
- The service life of a geomembrane liner is extremely sensitive to the time-temperature history it experiences, with predicted service lives ranging between thousands of years and a few decades depending on this history. This range illustrates the important role that time-temperature history could play in terms of geomembrane service life and highlights the need for long-term monitoring of landfill liner temperature. It also demonstrated the significant potential effect of even a relatively short period of time at elevated temperatures above 50°C.

HDPE geomembranes can potentially have a very short or very long service life, depending on (a) the choice of geomembrane and its consequent properties, (b) the configuration of the liner system, and (b) the time-temperature history of the geomembrane liner. This paper demonstrates that more attention needs to be paid to these issues than has been common in the past.

ACKNOWLEDGEMENTS

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