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Impact of landfill liner time–temperature history on the service life of HDPE geomembranes

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ABSTRACT

The observed temperatures in different landfills are used to establish a number of idealized time–temperature histories for geomembrane liners in municipal solid waste (MSW) landfills. These are then used for estimating the service life of different HDPE geomembranes. The predicted antioxidant depletion times (Stage I) are between 7 and 750 years with the large variation depending on the specific HDPE geomembrane product, exposure conditions, and most importantly, the magnitude and duration of the peak liner temperature. The higher end of the range corresponds to data from geomembranes aged in simulated landfill liner tests and a maximum liner temperature of 37 °C. The lower end of the range corresponds to a testing condition where geomembranes were immersed in a synthetic leachate and a maximum liner temperature of 60 °C. The total service life of the geomembranes was estimated to be between 20 and 3300 years depending on the time–temperature history examined. The range illustrates the important role that time–temperature history could play in terms of geomembrane service life. The need for long-term monitoring of landfill liner temperature and for geomembrane ageing studies that will provide improved data for assessing the likely long-term performance of geomembranes in MSW landfills are highlighted.

1. Introduction

Composite liners, typically involving a geomembrane (GM) over a geosynthetic clay liner or compacted clay liner have been shown to be very effective at limiting the escape of gas, the leakage of leachate and diffusion of contaminants to ground-water systems while the geomembrane remains relatively intact (Rowe et al., 2004; Bouazza et al., 2008; El-Zein and Rowe, 2008; Saidi et al., 2008). However, the temperature in a landfill, and especially that at the base and side slope of a landfill, has the potential to impact the long-term performance of geomembrane in the composite liner systems (Rowe, 2005).

The biodegradation of municipal solid waste (MSW) or the heat of hydration of incinerated bottom ash are the primary factors contributing to the generation of heat in a landfill (Klein et al., 2001; Yoshida and Rowe, 2003; Rowe, 2005; Yesiller et al., 2005; Koerner et al., 2008). The temperature in a landfill, and hence the liner temperature, depends on various factors such as the type of waste, moisture content of waste, biomass content, rate of waste filling, thickness of waste, and the climatic condition of the region (Brune et al., 1991; Collins, 1993; Lanini et al., 2001; Hanson et al., 2005; Rowe, 2005).

The decomposition of waste occurs both aerobically and anaerobically with the aerobic decomposition phase starting before the anaerobic decomposition phase although both phases may be active at different locations in a landfill (depending on when and where waste was placed). The chemical reactions that occur during the microbial decomposition of a major component of solid waste (e.g., glucose) are shown in Eqs. (1) and (2), respectively (Collins, 1993).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 1770\ \text{kJ/mol} \quad \text{(aerobic)} \quad (1)$$

$$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2 + 100\ \text{kJ/mol} \quad \text{(anaerobic)} \quad (2)$$

The heat production during the aerobic and anaerobic decompositions of waste are 1770 and 100 kJ mol^{-1}, respectively. Dach and Jager (1995) reported maximum temperatures of 85 and 70 °C in the waste due to the aerobic and anaerobic decomposition of waste, respectively. Both thermophilic and mesophilic microorganisms are responsible for the decomposition of municipal solid waste and the optimum range of temperature for their growth is about 50–60 and 30–40 °C, respectively (Cecchi et al., 1993; Zanetti et al., 1997).

Rowe (2005) provided the first assessment of the likely effect of liner temperature history on Stage I (antioxidant depletion) of the service life of a geomembrane. This paper expands on that initial work based on several years of additional field data relating to liner temperature and for the first time also addresses all three stages of

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the service life of geomembranes based on recently published geomembrane ageing data. Thus the objective of this paper is to examine data related to landfill liner temperatures and then to use idealized temperature histories, guided by this data, to predict the service life of a primary HDPE geomembrane liner used as part of a modern engineered barrier systems for a number of scenarios and hence provide some insight regarding the long-term performance of these systems.

2. Data regarding landfill liner temperature

Several researchers have investigated temperature in the main body of the waste as well as at the base of the landfills. Unfortunately in most cases there is not sufficient data to fully define the time–temperature history however, imperfect as it is, this data does provide context for the present discussion and is summarized in Table 1. The table includes the landfill location since climate can affect temperature and especially the rate of temperature increase, the leachate level (since this may also affect temperature), the time after the initiation of landfilling when the observation was made (to the extent known), the maximum reported waste temperature (where known) at the time (or in the stated period), the liner temperature (where known) and the reference. In some cases the time is measured post closure (pc) and the actual age of the waste above the monitoring point is unknown. For example the landfill in Hannover, Germany was operated for 44 years and the data was obtained 12 years post closure; so the waste age is unknown and could be anywhere from 12 to 56 years old above the location being monitored. In a number of cases there is good detail regarding the time–temperature history and this is also discussed below.

When discussing waste and liner temperature it should be remembered that in addition to the variables noted above, the temperature and rate of change in temperature with time can also depend on rates of waste filling (Yesiller et al., 2005), the waste temperature at the time of placement (Yesiller et al., 2005; Farquhar and Rovers, 1973), leachate recirculation (Needham and Knox, 2008), and moisture addition (Koerner et al., 2008).

Yoshida and Rowe (2003) described the observed and predicted temperatures at the base of the Tokyo Port Landfill in Japan (Fig. 1; Table 1). Temperature monitoring commenced about 7 years after commencement of waste placement. At this time the height of leachate was reported to be about 18 m above the base. This leachate level decreased to about 11 m over the next 7 years and then remained relatively constant to the end of the reporting period. The temperatures 2.5 m above the base and at the base were reported to be 50 °C (measured) and 45 °C (predicted), respectively, after 7 years of landfilling, remained relatively constant for the next 6–10 years, and decreased slowly afterwards. Modelling that was calibrated against the observed temperatures in the waste gave predicted top of liner temperatures as shown in Fig. 1 with a peak value of 45 °C at about 10 years reducing to about 30 °C at 30 years.

Koerner et al. (2008) monitored the temperatures on the primary geomembrane at two landfill cells designated as "dry" and "wet" (Fig. 2). Liquids were added to the wet cell to accelerate the biodegradation of waste; however, no liquids were added in the dry cell. The temperature of the dry cell was more or less constant (e.g., 20 °C) for the first 5–6 years of landfilling after which time the temperature increased to 33 °C after about 7 years and has remained relatively steady for the next 6 years. The temperature of the wet cell increased rapidly to 50 °C after 5.7 years of landfilling. The temperature may be leveling off at about 50 °C but could also still increase further and both possible scenarios will be considered.

Table 1
Some landfill temperature data (NB: all are MSW landfills except for the ashfill in Ingolstadt, Germany).

Location	Waste thickness (m)	Leachate level (m)	Time (years)	Waste temperature (°C)	Liner temperature (°C)	Reference
Altwarmbüchen, Germany	40	–[a]	4pc[b]	–	38	Brune et al. (1991)
Pickering, ON, Canada	60	20	11	60	–	Bleiker (1992)
Hannover, Germany	60	6	12pc[b]	65	60	Collins (1993)
	60	4	12pc[b]	64	30	
Bavaria, Germany	20	<0.1	6–10	44–64	35–53	Gartung et al. (1999)
South of France	20	<0.1	1	50–60	–	Lefebvre et al. (2000)
Alaska, USA	51	–	10	33	13	Yesiller et al. (2005)
Michigan, USA	31	–	5–7	56	–	
New Mexico, USA	19	–	5	32	30	
British Columbia, Canada	19	–	4	43	15	
Croydon, UK	23	17	6	–	32–40	Needham and Knox (2008)
Tokyo, Japan	35	18	7	66	45	Fig. 1 and Yoshida and Rowe (2003)
	35	11	30	–	30	
Philadelphia, PA, USA, dry	70	<0.1	0–6	–	20	Fig. 2 and Koerner et al. (2008)
	70	<0.1	13	–	33	
Philadelphia, PA, USA, wet	70	<0.1	6	–	50–54	
Stage 1, Maple, ON, Canada	65	1	0–5	–	12	Fig. 3
		7	14	–	37	
		7	14–21	–	37	
Stage 2, Maple, ON, Canada	65	1	0–3	–	9–11	
		1–5	18	–	35–36	
Stage 3, Maple, ON, Canada	65	<0.3	0–6	–	10	
		<0.3	16	–	37	
Stage 4, Maple, ON, Canada	65	<0.3	1	–	7	
		<0.3	1–15	–	7–35	
Ingolstadt, Germany (ashfill)	9	<0.3	0.25	87	23	Klein et al. (2001)
	9	<0.3	1.5	64	46	
	9	<0.3	3	43	40	

[a] – = Not known.
[b] pc = Post closure.

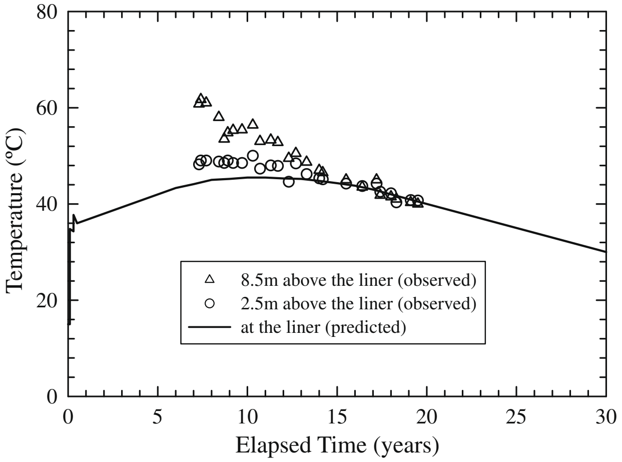

Fig. 1. Variation in temperature with time at three elevations in the Tokyo Port Landfill, Japan (data replotted from Yoshida and Rowe (2003)).

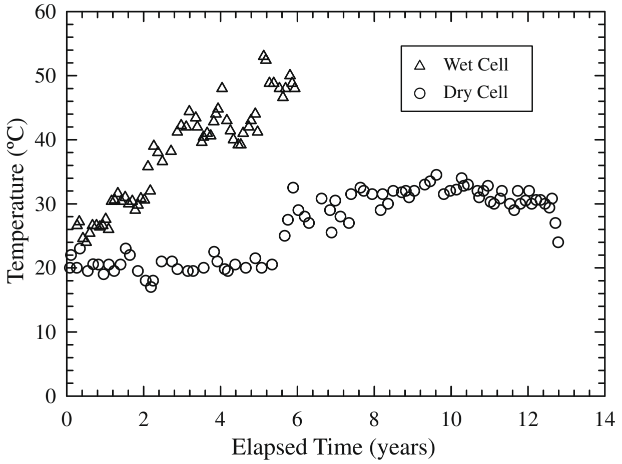

Fig. 2. Variation in average temperature with time for the dry and wet cells of the Philadelphia, USA landfill (data replotted from Koerner et al. (2008)).

Klein et al. (2001) reported temperatures at the base liner for a municipal solid waste incineration bottom ash landfill for a period of about 3 years. Exothermic reactions within the waste gave rise to a maximum temperature of 87 °C at 6 m above the base of the landfill after 3 months of disposing of the bottom ash. After reaching the maximum temperature, the temperature decreased to about 43 °C by the end of the reported period (i.e., 33 months). The temperature at the liner increased to about 46 °C after 17 months of ash placement and was about 40 °C after 3 years. This example illustrates the need to consider temperature effects even for landfills that do not have organic waste.

The Keele Valley Landfill (KVL) in Maple, ON, Canada provides a significant amount of liner temperature data. The disposal of waste started in 1983 and continued until closure at the end of 2002. The landfill covers almost 100 hectares and was constructed in four stages (referred to as Stages 1–4). The leachate collection system for Stages 1 and 2 comprised French drains at a spacing of 65 m while that for Stages 3 and 4 comprised a continuous granular drainage blanket.

Fig. 3 shows the variations in liner temperature and leachate head with time at four locations in Stages 1–4 to December 2006. Typically there is a period of gradual increase in temperature with time, followed by a period of relatively rapid increase in temperature with time and then a leveling off of the temperature at about 35–37 °C.

Fig. 4 shows the variations in temperature with time at 12 monitoring locations in Stages 3 and 4 where the leachate head was less than 0.3 m. The temperature was between about 7 and 20 °C within the first 8 years but then increased rapidly to about 37–40 °C over the next 4–6 years and has remained relatively constant to the end of the monitoring period. The time lag between the installation of the monitors and the onset of temperature increase is probably due to the time required for the accumulation of sufficient moisture in the waste to allow significant biodegradation and hence heat generation and conduction to the liner (Rowe, 2005).

Based on the foregoing 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).

3. Idealized temperature variation in a landfill

To incorporate the landfill liner temperature history in the prediction of the service life of an HDPE geomembrane, it is necessary to assume an idealized temperature variation with time such as that shown in Fig. 5. The temperature at the base of the landfill is assumed to start at T_0 (typical ground temperature in the absence of landfilling) 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_0 at time t_4 and remained constant thereafter (Fig. 5). Table 2 summarizes 22 idealized landfill liner time–temperature histories based, where possible, on data from four different landfills located in Canada, Germany, Japan, and the USA. Typically several idealized cases are related to each landfill data set to reflect possible scenarios in the time periods when data is not available (e.g., the period at maximum liner temperature is generally not well defined and in no case has the temperature yet gone back to the original ground temperature).

4. Prediction of geomembrane service life based on landfill liner temperature history

The service life of HDPE geomembranes is normally evaluated using a three-stage degradation model (Hsuan and Koerner, 1998) as illustrated in Fig. 6. According to this model, the service life of HDPE geomembranes is considered to be given by the sum of the time in each of the following three stages: Stage I – depletion of antioxidants, Stage II – induction time to onset of polymer degradation, and Stage III – degradation to failure (failure is considered when a particular GM property decreased to the 50% of the initial or the specified value). It is acknowledged that the boundaries between stages I, II, and III are not, in practice, as distinct as implied by Fig. 6 and the end of Stages II and III may vary depending on the parameters being considered (e.g., tensile break strength, tensile break strain, stress crack resistance, etc.). Since stress cracking is the mode of final failure, the authors consider this to be the most appropriate determinant of end-of-life when the data is available.

The Appendix describes the methods used in predicting the duration of each stage of GM service life considering the idealized liner temperature history shown in Fig. 5 and Sections 5–7 summarize the findings. Since not all geomembranes are the same and since the method of ageing can also affect the service life of the

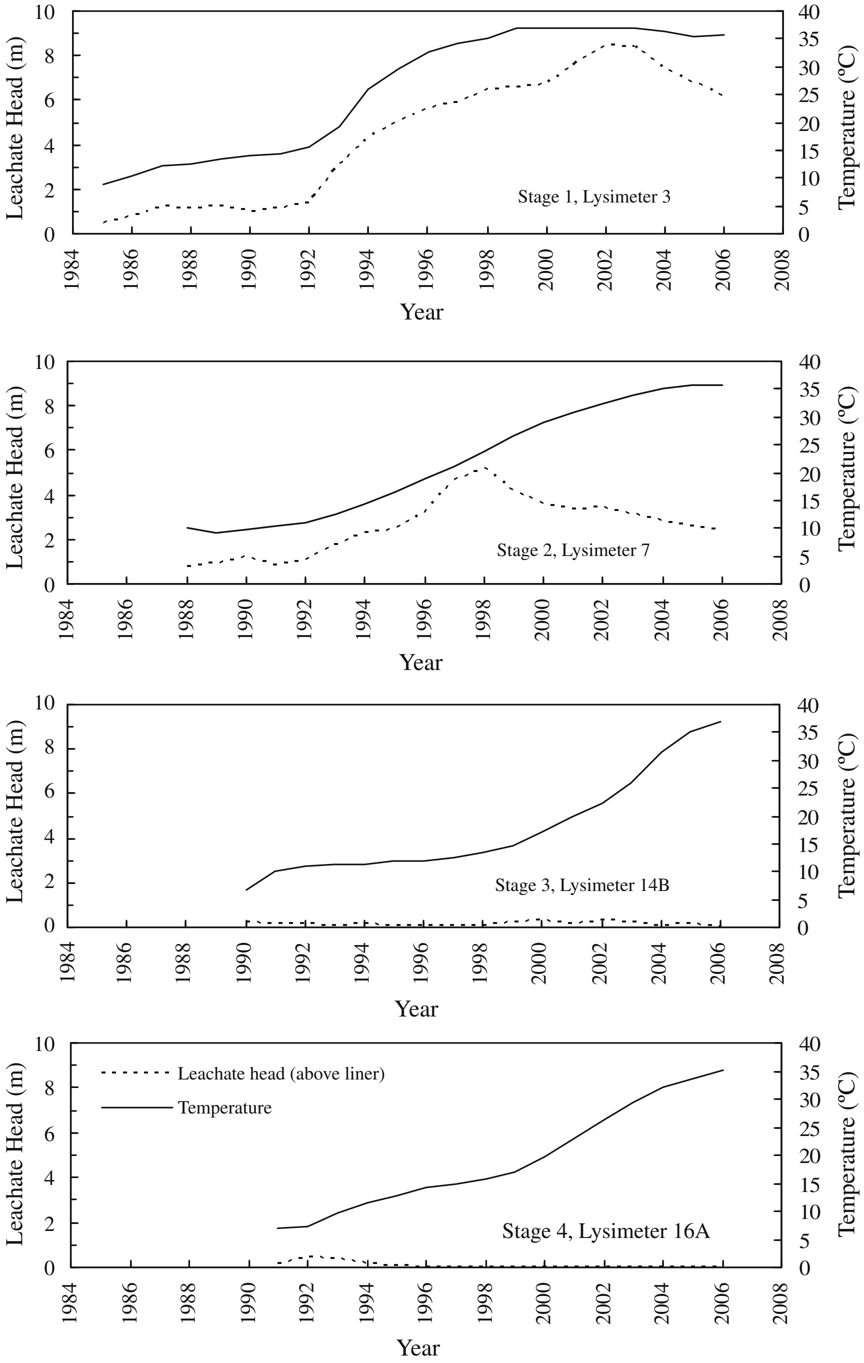

Fig. 3. Variation in temperature and leachate head at four locations in the Keele Valley Landfill to December 2006 (data courtesy of City of Toronto; modified from Rowe (2005) with additional data added).

geomembrane, consideration will be given to eight cases involving six different geomembranes (Table 3) for which data is available with respect to Stage I of the service life. The data from the ageing tests cited in Table 3 is used to make the predictions presented in Sections 5–7. The geomembranes GM1, GM2, and GM3 were manufactured by GSE Lining Inc., TX, USA and the geomembranes GM4, GM5, and GM6 were manufactured by Solmax International, Quebec, Canada. It should be noted that the geomembranes GM1a and GM1b are the same geomembrane but the method of ageing is different. Similarly, geomembranes GM4a and GM4b are the same geomembrane but the method of ageing is different. For ageing method "A" the geomembrane was immersed in simulated MSW leachate (no applied stress). This is the most common ageing tests reported in the literature (Hsuan and Koerner, 1998; Sangam and Rowe, 2002; Gulec et al., 2004; Rowe, 2005; Rowe et al., 2008, 2009) but is likely to be over conservative since it implies that the geomembrane is exposed to leachate on both sides whereas for the geomembrane away from holes in a composite landfill liner, the top may be exposed to leachate but the bottom is usually in contact with a clay liner and not leachate (Rowe, 2005). Ageing method "B" (Rowe and Rimal, 2008) attempted to address this concern and is for a simulated composite liner with the top face of the geomembrane exposed to leachate and the bottom face exposed to a hydrated GCL. In this case there was no

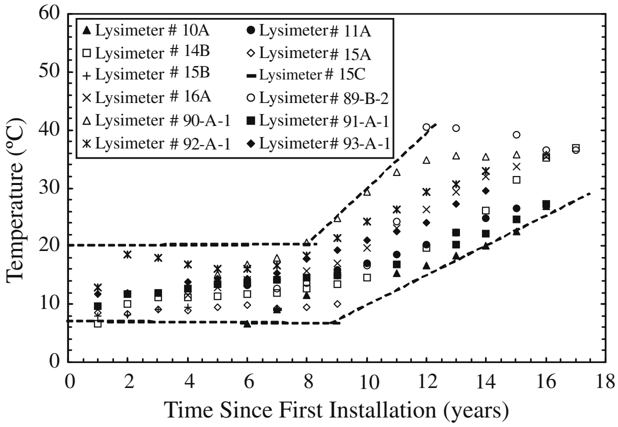

Fig. 4. Variation in temperature with time at different monitoring locations where the leachate head is less than 0.3 m (data courtesy of City of Toronto; modified from Rowe (2005) with additional data added).

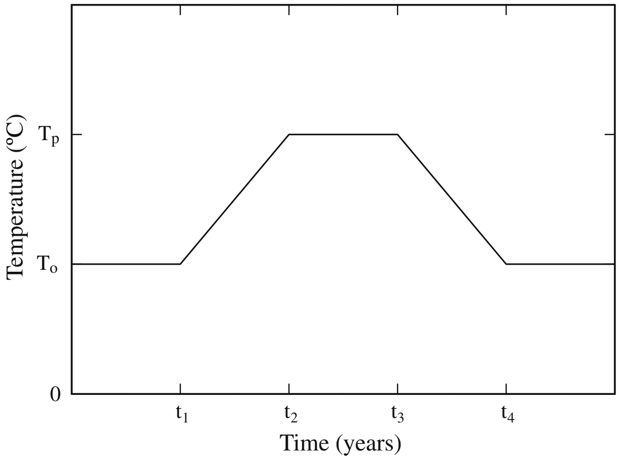

Fig. 5. Idealized temperature variation with time in a landfill.

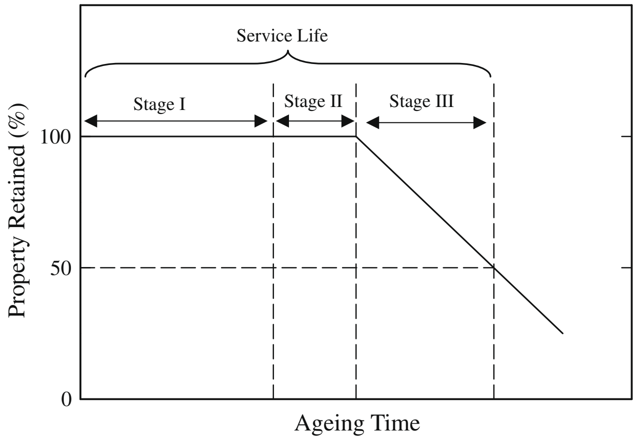

Fig. 6. Three conceptual stages in chemical ageing of HDPE geomembranes: Stage I – antioxidant depletion time, Stage II – induction time to onset of polymer degradation, and Stage III – time to reach 50% degradation of a particular geomembrane property (modified from Hsuan and Koerner (1998)).

applied stress and hence while better than method A, this approach may be unconservative since any effect of applied stress is neglected. Ageing method "C" (Islam, 2009) is the most realistic and involves a full simulated composite liner (from bottom up: a sand foundation layer, geosynthetic clay liner (GCL), geomembrane, geotextile protection layer, and gravel drainage layer with circulating simulated MSW leachate) subject to a 250 kPa stress applied to the gravel leachate collection layer.

5. Prediction of time to complete Stage I – depletion of antioxidants

As described in the Appendix, the antioxidant depletion time can be calculated for time temperature histories as shown in Fig. 5. To demonstrate the effect of the different time histories (and assumptions where data is not available), all 22 idealized cases were used to predict the antioxidant depletion time (Stage I) as summarized in Table 4.

The results presented in Table 4 demonstrate the importance of the method of ageing of the geomembrane on the predicted geomembrane service life. The typical method adopted in the literature for ageing of geomembranes is by immersion in the

Table 2
Liner temperature histories examined.

Case	t_1 (years)	t_2 (years)	t_3 (years)	t_4 (years)	T_0 (°C)	T_p (°C)	Remarks
1	3	16	26	40	10	35	Idealized based on Lysimeter 7, Fig. 3
2	3	16	26	50	10	35	Idealized based on Lysimeter 7, Fig. 3
3	3	16	50	64	10	35	Idealized based on Lysimeter 7, Fig. 3
4	8	14	20	40	10	37	Idealized based on Fig. 4
5	8	14	40	60	10	37	Idealized based on Fig. 4
6	6	7	20	40	20	33	Idealized based on dry cell, Fig. 2
7	6	16	25	45	20	33	Idealized based on dry cell, Fig. 2
8	5	14	20	50	12	37	Idealized based on Lysimeter 3, Fig. 3
9	5	14	40	70	12	37	Idealized based on Lysimeter 3, Fig. 3
10	0	6	14	24	20	50	Idealized based on wet cell, Fig. 2
11	0	6	20	30	20	50	Idealized based on wet cell, Fig. 2
12	0	6	30	40	20	50	Idealized based on wet cell, Fig. 2
13	0	8	20	30	20	60	Idealized based on wet cell, Fig. 2
14	0	8	30	40	20	60	Idealized based on wet cell, Fig. 2
15	0	8	40	50	20	60	Idealized based on wet cell, Fig. 2
16	0	10	30	40	20	70	Idealized based on wet cell, Fig. 2
17	0	2	10	20	20	43	Idealized based on Klein et al. (2001)
18	0	2	30	40	20	43	Idealized based on Klein et al. (2001)
19	0	8	14	30	15	45	Idealized based temperature at the liner, Fig. 1
20	0	8	14	40	15	45	Idealized based temperature at the liner, Fig. 1
21	0	8	18	30	15	50	Idealized based temperature at 2.5 m above the liner, Fig. 1
22	0	8	18	40	15	50	Idealized based temperature at 2.5 m above the liner, Fig. 1

Table 3

Initial properties of the geomembranes along with the ageing conditions for which geomembrane service life was predicted [A: immersion in leachate; B: simulated composite liner with no stress, top face of the geomembrane exposed to leachate and the bottom face exposed to hydrated GCL; C: simulated composite liner by applying 250 kPa stress, top face of the geomembrane exposed to leachate and the bottom face exposed to hydrated GCL; X: synthetic leachate consisted of inorganic nutrients, volatile fatty acids, surfactant, trace metals, and reducing agent (similar to the leachate of Keele Valley Landfill in Ontario); Y: synthetic leachate consisted of surfactant, trace metals, and reducing agent].

Geomembrane type	Thickness (mm)	Ageing condition	Leachate type	Significant initial properties					Reference
				Std-OIT (min) [ASTM D3895]	HP-OIT (min) [ASTM D5885]	MI (g/10 min) [ASTM D1238]	Tensile break strain (%) [ASTM D6693]	Stress crack resistance (h) [ASTM D5397]	
GM1a	1.5	A	X	135	660	0.55[a]	930	3740	1
GM1b	1.5	B	X	135	660	0.55[a]	930	3740	1
GM2	2.0	A	X	133	380	0.42[a]	1023	5220	2
GM3	1.5	A	Y	174	903	0.43[a]	945	1000	3
GM4a	1.5	A	Y	135	244	14.3[b]	828	1432	3
GM4b	1.5	C	Y	135	244	14.3[b]	828	1432	3
GM5	2.0	A	Y	150	265	11.1[b]	787	1252	3
GM6	2.5	A	Y	136	235	14.5[b]	701	624	3

Reference: (1) Rowe and Rimal (2008), (2) Rimal (2009), and (3) Islam (2009).

[a] Using 2.16 kg load in accordance with ASTM D1238.

[b] Using 21.6 kg load in accordance with ASTM D1238.

Table 4

Time to complete Stage I or OIT depletion (numbers rounded to two significant digits).

Case	Antioxidant depletion time[a] (years)							
	GM1a	GM1b	GM2	GM3	GM4a	GM4b	GM5	GM6
1	21	190	19	27	23	730	27	32
2	21	170	19	27	23	680	27	31
3	21	50	19	27	23	380	27	30
4	20	210	19	28	23	750	28	37
5	20	46	19	25	22	390	25	28
6	17	95	16	25	20	250	25	30
7	20	110	18	28	23	270	27	31
8	19	140	18	25	21	530	25	29
9	19	44	18	24	21	250	24	27
10	7	17	8	9	8	61	9	10
11	7	16	8	9	8	19	9	10
12	7	16	8	9	8	19	9	10
13	7	12	8	8	8	12	8	9
14	7	12	8	8	8	12	8	9
15	7	12	8	8	8	12	8	9
16	7	11	8	8	8	10	8	9
17	7	70	8	10	8	200	10	13
18	7	22	8	10	8	30	10	12
19	10	66	10	13	11	270	13	14
20	10	33	10	13	11	200	13	14
21	9	18	9	11	10	21	11	12
22	9	18	9	11	10	21	11	12

[a] Antioxidant depletion times are based on Std-OIT test.

fluid/leachate of interest (method "A" in this paper). In all cases where the geomembrane was aged by immersion in leachate (GM1a, GM2, GM3, GM4a, GM5, and GM6) the time to antioxidant depletion was relatively small (7–37 years depending on the case). In contrast, for the geomembranes aged in simulated composite liner systems (GM1b and GM4b) the time to antioxidant depletion ranged between relatively small values (a low value of 10 years for Case 16) and high values (210 and 750 years for Case 4).

The results obtained using conventional immersion may approximate the conditions in that portion of the geomembrane liner where there is a hole and hence leachate is already on both sides of the geomembrane. The results shown in Table 4 indicate that the antioxidants depletion time in these areas is relatively short for all the time–temperature histories examined.

The predications of antioxidant depletion based on leachate immersion tests (Table 4) are too conservative for geomembrane that is intact and hence leachate is only in contact with the upper portion of the geomembrane. Since this case represents the bulk of a newly constructed composite liner, the following discussion of antioxidant depletion will focus on the results for simulated composite liners (GM1b and GM4b).

For simulated landfill conditions, the time that the temperature remains at or near the peak (t_3–t_2) can have a critical effect on the time to antioxidant depletion (Table 4). For example increasing the time the temperature remained at 35 °C from 10 years (Case 1) to 34 years (Case 3) resulted in a reduction in antioxidant depletion time from 190 to 50 years for GM1b and from 730 years to (a still long) 380 years for geomembrane GM4b. Thus the service life of the geomembrane is sensitive to a time period that could vary form one landfill to another but for which there is very little data at present. These results also clearly demonstrate that not all geomembranes are the same. In one case the time to antioxidant depletion is relatively small while in the other it is still quite long.

Cases 6–7 are based on the temperature of the dry cell of the Philadelphia landfill (Fig. 2). It is assumed that the peak temperature of about 33 °C would only be sustained for 9 years (Case 7) to 13 years (Case 6). Under these circumstances the time to antioxidant depletion (95–270 years) is much longer than the time assumed for all heat to be dissipated (40–45 years) and for these scenarios the geomembrane can be expected to perform well. However, the situation is not so good when the temperature increases to 43 °C or higher as discussed below.

Cases 10–16 are based on the temperature of the wet cell of the Philadelphia landfill (Fig. 2) where moisture was added to the waste. For Cases 10–12, where the average peak temperature is assumed to be 50 °C, the time that the temperature remains at 50 °C becomes critical. In Case 10 where the time at peak is assumed to be 8 years with full temperature stabilization in 24 years, the times to antioxidant depletion (17–61 years) are similar to, or in excess of, the time to temperature stabilization (24 years) and hence the geomembrane service life is likely to be adequate since the expected times in Stages II and III are quite long at 20 °C (or less) as will be discussed in more detail later. However, if the temperature were to remain at peak for 24 years (Case 12) the time to antioxidant depletion drops to 16–19 years and there is a need to examine the other stages of the service life to assess whether the geomembrane service life would be adequate. If the peak temperature goes to 60 °C then antioxidant depletion occurs at 12 years (Cases 13–15), only 4 years after the peak temperature is reached and the service life of the geomembrane requires very careful examination. These results highlight the need for considerable caution in designing landfills where the liner temperature could get to 50–60 °C (or higher).

As illustrated by Cases 17–22, even at temperatures of 43–50 °C a relatively short time (6–10 years) at the peak temperature and the rate of decrease in temperature with time has a profound effect in terms of depleting the antioxidants in the geomembrane.

In summary, for a geomembrane aged in a simulated landfill liner system (GM4b) the antioxidant depletion times varied from 10 to 750 years for the 22 time histories examined, with the higher end of the range (750 years; Case 4) corresponding to an idealized case based on the temperatures observed at monitors in the KVL where leachate head was less than 0.3 m and the average peak temperature was 37 °C (Fig. 4). The lower end of the range was 10 years for a peak liner temperature of 70 °C (Case 16) and 12 years for a peak liner temperature of 60 °C (Cases 13–15). At the longer end of this spectrum, the contaminating lifespan (Rowe et al., 2004) can be expected to be reached (and hence the geomembrane is no longer needed to protect the environment) while the geomembrane is still in Stage I (i.e., antioxidants are still not depleted). However, at the shorter end of the spectrum where antioxidants are depleted in 10–30 years (Cases 11–16, 18, 21, and 22), the length of time in Stages II and III will be quite critical to the long-term performance of the geomembrane.

Relative to the likely contaminating lifespan of modern landfills (Rowe et al., 2004), quite short times (7–21 years for GM1a and 8–23 years for GM4a) are predicted for all cases (1–22) for a geomembrane with leachate on both sides of the geomembrane (as would be expected near holes in a geomembrane). Thus a failure mechanism for geomembranes that requires consideration involves the progressive breakdown of the geomembrane (probably by stress cracking) in areas of high tensile strain due to wrinkles and/or inadequate geomembrane protection (Take et al., 2007; Brachman and Gudina, 2008a,b) where leachate has managed to get below the geomembrane due to the presence of a hole at the time of construction (especially a hole in a wrinkle; see Rowe (2005)). Once a new crack appears, leachate will spread out further and cause more accelerated ageing of geomembranes that had previously only had leachate on one side and hence previously slow depletion for many of the temperature histories examined. Thus to allow an assessment of the potential risk for this mechanism, the length of time in Stages II and III will be quite critical for all the time temperature histories examined.

The results discussed above highlight the significant impact of the peak temperature, the time at peak temperature, and the time it will take to get from peak temperature back to ground temperature. While there is limited data relating to peak temperature (as discussed) there is a paucity of data regarding the time at peak temperature, and the time it will take to get from peak temperature back to ground temperature. This emphasizes the need for more and longer-term monitoring data related to landfill liner temperature. It also emphasizes the need for information relating to the likely time in Stages II and III as discussed in the following subsections.

6. Prediction of time to complete Stage II – induction time

The duration of Stage II can be predicted at a temperature of interest using the Arrhenius time–temperature relationship as described in the Appendix. To accurately establish Stage II for a given geomembrane and exposure condition it is necessary to first deplete the antioxidants (i.e., complete Stage I since this defines the beginning of Stage II) and, second, to see the initiation of a change in the physical properties of the geomembrane (since this signals the end of Stage II) at three (or more) temperatures. Given the quality of all the geomembranes tested, this takes a long time at all but the highest temperature examined. Thus Stage II has not been completed at three elevated laboratory temperatures for any of the geomembranes exposed to simulated MSW leachate that have been studied to date (Table 3) despite the fact that some of the tests have been running for over a decade. Only for one geomembrane (GM3) has Stage II been completed at two temperatures (85 and 70 °C) and for this case the parameters were obtained from a two point approximation. For geomembranes GM2, GM4a, GM5 and GM6, Stage II has been completed only at 85 °C. For these geomembranes the duration of Stage II was calculated using the laboratory data at 85 °C and activation energy of 75 kJ mol^{-1} as reported by Viebke et al. (1994) for air–water exposed polyethylene pipe.

Table 5 presents the time to complete Stage II for the six geomembranes for three of the time–temperature histories presented in Table 2. In all three cases the liner temperature was assumed to reduce back to the original ground temperature 40 years after the start of landfilling. The first two cases (Cases 1 and 4) were selected to illustrate the effect of some temperature history variability for the case where the peak temperature is 35–37 °C and the third case (Case 14) was selected to illustrate the potential implications of a much higher peak temperature (60 °C). The predictions of Stage II time were based on the available data for both the tensile break strain and stress crack resistance of the geomembranes that had been aged in contact with simulated MSW leachate and the minimum time is given in Table 5. The stress crack resistance of an aged geomembrane specimen was evaluated according to the single point-notched constant tensile load test (ASTM D5397) using dumbbell-shaped specimens immersed in a solution containing 10% Igepal® CO630 and 90% water at 50 °C. For geomembranes GM1a, GM1b, and GM4b, Stage II was not monitored in the laboratory experiments and for the geomembrane GM3, stress crack resistance was not monitored in the laboratory experiments. Since there was no Stage II data for GM1 it is not considered in Table 5. Although there was no Stage II data for GM4 in a simulated liner, data was available for immersion of that geomembrane in leachate and hence to obtain an estimate of Stage II for the geomembrane GM4b, the Stage II experimental data for GM4a was used for predicting Stage II times for this geomembrane. Even though the same Stage II parameters were used for GM4a and GM4b, the predictions of Stage II are different due to the different length of Stage I and hence the different time histories in Stage II for the two scenarios. Very limited experimental data was available to calculate Stage II times and consequently one should be cautious in using the times presented in Table 5. Nevertheless, the results do provide significant insight regarding the effect of different time histories on the geomembrane service life.

Table 5
Estimated time to complete Stage II for some selected cases (rounded to two significant digits). *Note:* time to complete Stage II depends on the temperature history remaining after completion of Stage I. The numbers given are to illustrate the potential effect of temperature history only. The estimates of Stage II will change as more data becomes available.

Geomembrane type	Time to complete Stage II (years)		
	Case 1	Case 4	Case 14
GM2[a]	290	310	4
GM3[b]	11	15	3
GM4a[a]	180	210	2
GM4b[c]	270	270	2
GM5[a]	280	300	3
GM6[a]	250	260	2

[a] Based on Stage II completion time at 85 °C in laboratory immersion experiments together with the activation energy of 75 kJ mol^{-1} used by Viebke et al. (1994) for air–water exposed polyethylene pipe.

[b] No data available for stress crack resistance for this GM so numbers are purely based on consideration of tensile properties. The reported Stage II times are based on Arrhenius properties obtained from Stage II completion times at 85 and 70 °C in laboratory experiments.

[c] No experimental data was available to predict Stage II time. The reported times are based on the geomembrane and testing condition for the geomembrane GM4a. Note that even though the same Stage II properties were used as for GM4a, the Stage II times are different because of the longer Stage I service live for GM4b than GM4a and hence the different time histories for Cases 1 and 4.

For the time–temperature histories 1 and 4 (Table 2) and GM4b, Stage I of the geomembrane service life (730 and 750 years; Table 4) was completed long after return to original ground temperature giving long times (270 years) for Stage II at this low temperature (10 °C). For the other geomembranes (GM2, GM3, GM4a, GM5, and GM6), by the end of Stage I there was either only a very limited time remaining at the peak temperature (e.g., 7 and 1 years for GM2 and Cases 1 and 4, respectively, or 3 years for GM4a and Case 1) or the landfill temperature was decreasing from the peak temperature. Thus, with the notable exception of GM3, the predicted time in Stage II is still in excess of 180 years. Based on the presently available data, it appears that the Stage II period for GM3 is substantially shorter than that for the other geomembranes, with predicted times of 11 and 15 years. It should be noted that for GM3, completion of Stage II has actually been observed in the laboratory at both 85 and 70 °C and hence these predictions are considered to be the most reliable of all the predictions (with the remainder being based on completion of Stage II at 85 °C and an assumed activation energy of 75 kJ mol^{-1} used by Viebke et al. (1994) for air–water exposed polyethylene pipe). However, the fact that Stage II has been completed at 70 °C for this geomembrane but not for the other geomembranes is also an indicator that this geomembrane may not have as good long-term performance as the other geomembranes. This again highlights the fact that not all geomembranes are the same and hence the need for testing to evaluate the long-term performance of geomembranes.

For time–temperature history 14 (Table 2), Stage I was completed when landfill temperature just reached peak temperature for GM2, GM3, GM4a, and GM5 and only shortly after reaching the peak for GM4b and GM6 (Table 4) allowing considerable time at 60 °C to reduce the Stage II component of the service life. Thus one would expect much shorter Stage II (and Stage III, discussed in the later section) times for all the geomembranes in Case 14 than for Cases 1 and 4. For Case 14, the Stage II times varied between 2 and 4 years (Table 5). Thus temperatures of 60 °C can have a profound impact on shortening both Stages I and II of the geomembrane service life.

7. Prediction of time to complete Stage III – degradation to failure

The calculation procedure for the prediction of Stage III time is the same as that of the Stage II time as described in the Appendix. The predictions of Stage III presented in this paper are far more speculative than for the other two stages simply because tests have not yet been running long enough to provide the data for modern geomembranes in a landfill application. Viebke et al.'s (1994) approximate degradation activation energy of 80 kJ mol^{-1}, which was used to make the following estimates, is based on measurements of the development of chain scission as a marker of polymer degradation rather than to a physical property such as stress crack resistance which is of most relevance to HDPE geomembrane service life. Thus, although not totally relevant to HDPE GMs, this approach is used because, at this time, we have nothing better to use. Not withstanding its shortcomings, this approach does allow us to illustrate the effect of time–temperature history which is the focus of the paper.

Table 6 shows the predicted time to complete Stage III for the same three cases for which Stage II times were calculated. The duration of Stage III for Case 14 (10–14 years) was substantially lower than for Cases 1 and 4 (1600–2300 years). This is because the geomembranes experienced higher temperatures in their Stage III service lives in Case 14 (20–60 °C) compared to Cases 1 and 4 where Stage III starts at original ground temperature (10 °C) for most of these cases (the exception being for GM3 and Case 1 where there are 2 years of declining temperature in Stage III).

Table 6
Time to complete Stage III for some selected cases (rounded to two significant digits). *Note:* the numbers given are to illustrate the potential effect of temperature history only. The estimates of Stage III will change as more data becomes available.

Geomembrane	Time to complete Stage III (years)		
	Case 1	Case 4	Case 14
GM2[a]	2200	2200	13
GM3[b]	2300	2300	14
GM4a[c]	2200	2200	14
GM4b[d]	2200	2200	14
GM5[c]	2000	2000	12
GM6[a]	1600	1600	10

[a] Based on Stage III completion time at 85 °C in laboratory immersion experiments together with the activation energy of 80 kJ mol^{-1} used by Viebke et al. (1994) for air–water exposed polyethylene pipe.

[b] No data available for stress crack resistance for this GM; therefore, the numbers are purely based on consideration of tensile properties. The reported times are based on Stage III completion time at 85 °C in laboratory immersion experiments together with the activation energy of 80 kJ mol^{-1} used by Viebke et al. (1994) for air–water exposed polyethylene pipe.

[c] Stage III has not been completed at any elevated temperature. The reported values are based on the time in Stage III at 85 °C in the laboratory immersion experiments together with the activation energy of 80 kJ mol^{-1} used by Viebke et al. (1994) for air–water exposed polyethylene pipe. Based on the approximation, the reported Stage III times are lower bound values.

[d] No experimental data was available to predict Stage III time. The reported times are based on the geomembrane and testing condition for the geomembrane GM4a.

8. Service life of HDPE geomembranes

The service life of HDPE geomembranes (Table 7) is calculated by adding the durations of Stages I–III presented in Tables 4–6. The service life varied between 20 and 3300 years, with the lower end of the range corresponding to a case where landfill temperature increases from 20 to 60 °C in 8 years and stays at 60 °C for 22 years and then decreased back to 20 °C in 10 years. While approximations are associated with all these predictions and not too much significance should be attributed to the specific values, the substantial difference in predicted time is significant and highlights the fact that the landfill time–temperature history is likely to be quite significant with respect to the service lives of HDPE geomembranes (and likely pipes). For situations like Cases 1 and 4, the geomembrane service life is likely to far exceed the contaminating lifespan (Rowe et al., 2004) of typical MSW landfills. In contrast, for situations like Case 14, the service life of the primary liner could well be reached within the contaminating lifespan and secondary containment may be necessary. This highlights the need to consider the possible effects of time–temperature history when designing MSW landfills.

Table 7
Service life for some selected cases (times greater than 100 years have been rounded to two significant digits; times less than 100 years have been rounded to nearest 5 years). *Note:* the three stages were added before rounding to get results in this table and hence the numbers below may not be exactly the same as the sum of the rounded numbers in Tables 3–5 because of rounding.

Geomembrane	Service life (years)		
	Case 1	Case 4	Case 14
GM2	2500	2500	25
GM3	2300	2300	25
GM4a	2400	2500	25
GM4b	3200	3300	30
GM5	2400	2400	25
GM6	1900	1900	20

9. Conclusions

The observed temperatures in different landfills were reviewed based on the data reported in the literature and augmented by new data from the Keele Valley Landfill in Maple, Ontario. The observed temperatures in the waste were reported in the range from 14 to 87 °C and at the liner from 7 to 60 °C. The temperature rose quickly in some landfills shortly after the start of the landfilling while in others it took substantially longer for the temperature to increase. However in all cases examined, temperatures in the range of 30–40 °C were encountered at the top of the landfill liner with typical landfilling operations. Substantially higher liner temperatures (50–60 °C) were observed in the case where there had been moisture augmentation. Monitoring has identified the peak temperature at a number of landfills; however, there is a paucity of data regarding how long the peak temperature will be maintained or how long it will take until the liner temperature returns to original ground temperature. Thus more and prolonged monitoring is required to provide this insight.

Based on the available field data for four landfills (located in Canada, Germany, Japan, and the USA), a number of idealized scenarios representing possible time–temperature histories were developed. A technique for estimating the service life of geomembranes based on the landfill liner time–temperature history was described and used to predict the service life of HDPE geomembrane using the three-stage degradation model. Of these three stages, the prediction of Stage I was the most reliable because of the availability of sufficient laboratory data. The Stage I times of the geomembranes were predicted to be between 7 and 750 years for the 22 idealized cases examined. The large variation in Stage I time is due to the variations in specific HDPE geomembrane products, exposure conditions and, most importantly, the magnitude and duration of the peak liner temperature. The higher end of the range corresponds to data from geomembranes aged in simulated landfill liner tests and a maximum liner temperature of 37 °C. The lower end of the range corresponds to a testing condition where geomembranes were immersed in a synthetic leachate and a maximum liner temperature of 60 °C.

The durations of Stages II and III of geomembrane service life were predicted to be between about 2–310 and 10–2300 years, respectively, depending on the geomembrane and the time–temperature history examined. The range illustrates the important role that time–temperature history could play in terms of geomembrane service life. The service life components of Stages II and III were based on very limited data and little significance should be assigned to the actual values; however, the effect of the different time–temperature histories is considered to be significant.

The total service life of the geomembranes were calculated by adding the durations of the three stages for respective geomembranes and found to be between 20 and 3300 years depending on the time–temperature history examined. Practitioners should use these service lives with extreme caution given the limitations of the predictions of Stages II and III highlighted in the paper. They are simply presented to illustrate the importance of the temperature time history. It is anticipated that over the next 5 years much better estimates of Stages II and III will be possible as results from ongoing studies at Queen's University become available. However the results do clearly demonstrate the need to consider the possible effects of time–temperature history when designing MSW landfills. The findings of the paper highlight the need for long-term monitoring of landfill liner temperature and the need for geomembrane ageing studies that will provide improved data for assessing the likely long-term performance of geomembranes in MSW landfills.

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Appendix. Method of calculation of Stages I–III of geomembranes service life

The depletion of antioxidants (Stage I) is normally evaluated using the following equation (Hsuan and Koerner, 1998):

$$OIT_t = OIT_0 e^{-st} \tag{3}$$

where OIT_t = OIT remained at any time t (min), OIT_0 = initial OIT (min), s = antioxidant depletion rate (month^{-1}), t = time (month). The antioxidant depletion rate at a temperature of interest is generally evaluated using the Arrhenius equation (Hsuan and Koerner, 1998) as shown in the following:

$$s = A \exp\left(\frac{-E_a}{RT}\right) \tag{4}$$

where E_a = activation energy (J mol^{-1}), R = universal gas constant (8.314 J mol^{-1} K^{-1}), T = absolute temperature (K), and A = a constant often called a collision factor. The parameters of Arrhenius equation (i.e., E_a and A) are normally evaluated from the plot of ln(s) vs. (1/T) drawn for at least three temperatures. The antioxidant depletion time is calculated from Eq. (3) by substituting the antioxidant depletion rate from Eq. (4).

Eq. (4) can be used directly to predict the antioxidant depletion rate at a constant temperature. In the case when the temperature is increasing, the average antioxidant depletion rate, s_{av}, should be used (Rowe, 2005) where:

$$s_{av} = \frac{\int_{t_1}^{t_2} A \exp\left\{\frac{-E_a}{R[T_0+\alpha(t-t_1)]}\right\} dt}{t_2 - t_1} \tag{5}$$

and α is the rate of temperature increase with time given by:

$$\alpha = \frac{T_p - T_0}{t_2 - t_1} \tag{6}$$

Similarly, when the temperature is decreasing the average antioxidant depletion rate can be written as:

$$s_{av} = \frac{\int_{t_3}^{t_4} A \exp\left\{\frac{-E_a}{R\left[T_p-\beta(t-t_3)\right]}\right\} dt}{t_4 - t_3} \tag{7}$$

where β is the rate of temperature decrease with time given by:

$$\beta = \frac{T_p - T_0}{t_4 - t_3} \tag{8}$$

The duration of Stage II (Fig. 6) can be predicted at a temperature of interest using the Arrhenius time–temperature relationship as follows:

$$\frac{1}{\xi} = A \exp\frac{-E_a}{RT} \tag{9}$$

where ξ is the duration of Stage II (years) and other parameters (e.g., A, E_a, R, and T) have already been defined. The parameters of the Arrhenius equation for Stage II (i.e., E_a and A) are normally evaluated from the plot of $\ln(1/\xi)$ vs. $(1/T)$ for experimental data obtained at different temperatures. Eq. (9) can be used directly in predicting the duration of Stage II when landfill temperature is constant. However, for the situation considered here where landfill temperature varied with time, the following procedure was used. Since Stage II does not begin until completion of Stage I, the starting time, t_I, and temperature, T_I, for the calculation of Stage II will vary depending on the geomembrane and case and can be deduced from Table 4. The period of varying temperature for Stage II was divided into small time increments Δt, with each time ($t_i = t_I + i\Delta t$) having a corresponding temperature T_i as defined by the temperature history (Table 2 and Fig. 5). For the first time in Stage II ($t_1 = t_I + \Delta t$), the duration of Stage II (ξ_1) was calculated from Eq. (9) at temperature T_1. The proportion of Stage II consumed during the time increment Δt was then calculated as $\Delta t/\xi_1$. The calculation procedure was repeated for the next increment of time Δt. For example, the duration of Stage II (ξ_2) at temperature of T_2 was calculated from Eq. (9) and the corresponding proportion of the Stage II property consumed (i.e., the depletion of time in Stage II for any geomembrane property, for example, stress crack resistance, tensile break strain, etc.) in the second time increment was calculated as $\Delta t/\xi_2$. The total Stage II property consumed by the end of the second time increment was ($\Delta t/\xi_1 + \Delta t/\xi_2$). The procedure was repeated until 100% of the Stage II property was consumed and the time to complete Stage II is taken by adding all the increments of time until Stage II is completed. The calculation procedure is the same for increasing, steady, or decreasing temperature.

To accurately establish Stage II for a given geomembrane and exposure condition it is necessary to first deplete the antioxidants (i.e., complete Stage I since this defines the beginning of Stage II) and, second, to see the initiation of a change in the physical properties of the geomembrane (since this signals the end of Stage II) at three (or more) temperatures. Given the quality of all the geomembranes tested, this takes a long time at all but the highest temperature examined. Thus Stage II has not been completed at three elevated laboratory temperatures for any of the geomembranes exposed to simulated MSW leachate that have been studied to date (Table 3) despite the fact that some of the tests have been running for over a decade. Only for one geomembrane (GM3) has Stage II been completed at two temperatures (85 and 70 °C) and for this case the parameters A and E_a in Eq. (9) were obtained from a two point approximation. For geomembranes GM2, GM4a, GM5, and GM6, Stage II has been completed only at 85 °C. For these geomembranes the duration of Stage II was calculated using the laboratory data at 85 °C and activation energy of 75 kJ mol^{-1} as reported by Viebke et al. (1994) for air–water exposed polyethylene pipe together with the following equations:

$$\frac{s_{85}}{s_T} = \exp\left(-\frac{E_a}{R}\left(\frac{1}{T_{85}} - \frac{1}{T}\right)\right) \tag{10}$$

$$\xi = \frac{s_{85}}{s_T} \times \xi_{85} \tag{11}$$

where T = temperature of interest (K), T_{85} = 85 °C = 358 K, s_T and s_{85} are the reaction rates of Stage II at temperatures T and T_{85}, respectively, ξ = Stage II time (years) at temperature T, and ξ_{85} = Stage II time (years) at 85 °C. Eqs. (10) and (11) are directly applicable for predicting the durations of Stage II at a constant temperature. For a situation when the temperature increases or decreases, the method described above was used. For example, after the first increment of time (Δt), the duration of Stage II (ξ_1) at temperature T_1 (corresponding to time $t_1 = t_I + \Delta t$) was calculated from Eqs. (10) and (11) at temperature T_1 and the proportion of the Stage II property consumed during that time increment would be calculated as $\Delta t/\xi_1$.

The calculation procedure for the prediction of Stage III time (Fig. 6) is the same as that of the Stage II time described previously. For none of the geomembranes examined has Stage III been completed in the laboratory experiments at more than one elevated temperature. Thus it was not possible to evaluate Stage III Arrhenius parameters for the geomembranes. Some geomembranes had completed Stage III at 85 °C (e.g., GM2 and GM3) while others were still in Stage III (GM4a and GM5) at 85 °C (Islam, 2009; Rimal, 2009; Rowe et al., 2009). Thus the duration of Stage III was calculated using the laboratory data at 85 °C and the activation energy of 80 kJ mol^{-1} used by Viebke et al. (1994) for air–water exposed polyethylene pipe together with Eq. (10) and hence:

$$\lambda = \frac{s_{85}}{s_T} \times \lambda_{85} \tag{12}$$

where T = extrapolation temperature (K), T_{85} = 85 °C = 358 K, s_T and s_{85} are the reaction rates of Stage III at temperatures T and T_{85}, respectively, λ = Stage III time at temperature T (years). For GM2, GM3, and GM6, λ_{85} = Stage III completion time at 85 °C (years) observed in the laboratory tests. For the geomembranes that have not yet completed Stage III (GM4a and GM5), λ_{85} = time in Stage III at 85 °C in the laboratory tests at the time of writing (and hence provides an underestimate of the Stage III completion time).

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