Service Life and Design Implications of HDPE Geomembranes at Elevated Temperature Landfills

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Abstract

Waste containment facilities can experience elevated temperatures for a variety of reasons such as hydration of combustion ash, aerobic biodegradation, and smoldering combustion. Elevated temperatures can reduce service life or effectiveness of geomembranes by accelerating antioxidant depletion and polymer degradation. A case history is presented to illustrate the potential effects of elevated temperatures and time-temperature history on a high-density polyethylene geomembrane and the associated reduction in service life or effectiveness. The impact of peak temperature, e.g., 60–80°C, the duration of peak temperatures (time-temperature history), and the time to complete antioxidant depletion were found to significantly reduced by increasing temperatures investigated. The effect of tensile strains, thickness, and leachate characteristics on estimated service life is also discussed.

INTRODUCTION

Municipal solid waste (MSW) landfills are required to install a barrier system to control the escape of contaminants from the waste to groundwater or surface water bodies. Landfill temperature is important because it can affect performance of various barrier system components, such as the geomembrane, low hydraulic conductivity compacted soil liner (LHCSL), geotextiles, geonet drainage component, and geosynthetic clay liner. In particular, elevated temperatures can reduce the service life of geomembranes (Rowe 2005) in both single and double composite liner systems (Rowe 2012; Jafari et al. 2014).

Elevated temperatures involve MSW temperatures increasing above a threshold, which begins to stress the biochemical decomposition processes, engineered barriers, and gas collection and leachate removal systems. MSW landfills with a gas collection and control system in accordance with federal regulations (40 Code of Federal Regulations (CFR), Part 60, Subpart WWW) are required to operate each gas extraction well with a gas wellhead temperature less than 55°C (131°F), which was part of the New Source Performance Standard (NSPS) in the Clean Air Act Extension of 1970. Several factors can lead to landfill temperatures exceeding 65°C, including aerobic decomposition, air intrusion, self-heating, partially extinguished surface fires, reactive wastes, spontaneous oxidation, and smoldering combustion. For example, MSW landfills have experienced elevated temperatures due to exothermic chemical reactions of industrial wastes, including aluminum production wastes (APW); incinerator ash; various hot wastes; bottom ash; tires; iron waste; steel mill slag; petroleum coke; flue gas desulfurization gypsum; fluidized bed combustion residues; lime kiln dust; and dried wastewater sludge. The

APW reaction involves the amphoteric reaction of metallic aluminum with water to produce hydrogen gas and heat (Stark et al. 2012). Observed temperatures of MSW landfills undergoing aluminum reactions range from 88°C to 110°C (Stark et al. 2012; Jafari et al. 2014). Given the occurrence of increasing waste and liner temperatures, this paper presents a landfill case study to determine the service life of a high-density polyethylene (HDPE) geomembrane subjected to elevated temperatures and provides a discussion of applicable engineering properties for assessing the service life of geomembranes.

EFFECT OF TEMPERATURE ON HDPE GEOMEMBRANES

HDPE geomembranes consist of, by weight percentage, 96–97% polyethylene resin, 2–3% carbon black, and approximately 0.5–1% antioxidants (Hsuan and Koerner 1998). Antioxidants are added to HDPE geomembrane formulations to reduce polymer degradation during processing and oxidation reactions during the initial stage of geomembrane service life (Hsuan and Koerner 1998). The degradation of HDPE geomembranes has been examined by a number of researchers (Hsuan and Koerner 1998; Sangam and Rowe 2002; Rowe 2005; Rowe and Rimal 2008) and is generally considered to consist of the following three stages: (Stage A) depletion of antioxidants; (Stage B) induction or start of polymer degradation; and (Stage C) polymer degradation and decrease in key physical properties (Hsuan and Koerner 1998). Figure 1 illustrates this conceptual definition of service life.

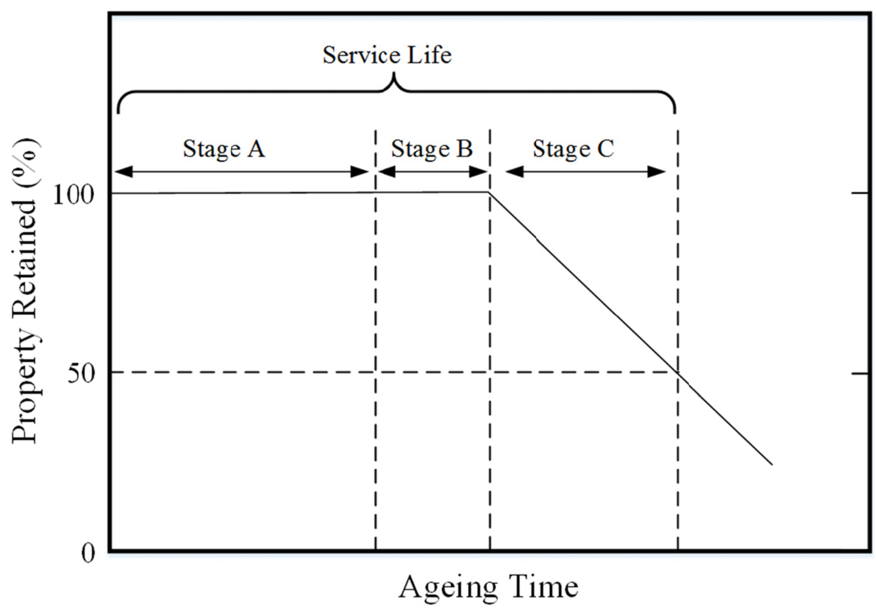

Figure 1. Conceptual diagram of service life and the three stages of degradation: Stage A antioxidant depletion; Stage B induction time; and Stage C polymer degradation and reduced physical and/or mechanical property (modified from Hsuan and Koerner 1998).

During Stage A, antioxidants present in the geomembrane are progressively volatized, diffused, or oxidized. The duration of Stage A is important because the active antioxidants protect the geomembrane polymer from degradation. During Stage B, polymer degradation commences but there is no measurable change in geomembrane engineering properties, even though the antioxidants have been significantly reduced or removed. Induction of polymer degradation continues in Stage B until the effects of the oxidation-induced scission of polyethylene chains becomes measurable. During Stage C, measurable changes in the engineering properties of the geomembrane occur (Koerner 1998) until the service life of the geomembrane is reached. The duration of each of the three stages is referred to as depletion time (Stage A), induction time (Stage B), and degradation time (Stage C), respectively. The service life of a geomembrane is the sum of the duration of these three stages. Figure 1 shows the decrease in service life for temperatures between 40ºC to 60ºC based on laboratory-simulated landfill liner systems experiments using 50% reduction in the tensile strength at break as the end of service life (Rowe 2005). Only the results for Stage A, or antioxidant depletion, are based on laboratory testing that simulates landfill disposal conditions. Stages B and C degradation are based on polyethylene pipe test results presented by Viebke et al. (1994). Although the estimated service life values assume a constant temperature, even a short duration of elevated temperature can significantly reduce HDPE geomembrane service life to several decades (Figure 2) and, by extrapolation, to as little as a few years at higher temperatures (Rowe and Islam 2009).

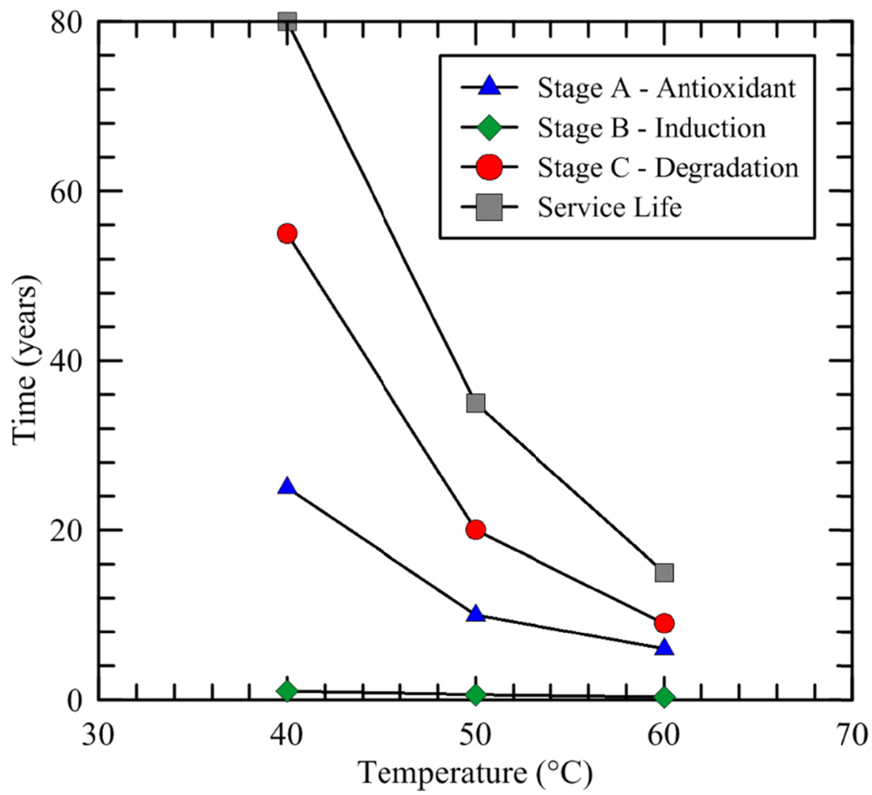

Figure 2. Duration of degradation Stages A-C and total service life based on 50% reduction in tensile strength at break (data from Rowe 2005).

PREDICTION OF HDPE GEOMEMBRANE SERVICE LIFE

The service life of HDPE geomembranes is normally evaluated using a three-stage degradation model, i.e., Stages A–C. The boundaries between Stages A–C are not, in practice, so distinct and the end of Stages B and C may vary depending on the parameters being considered, e.g., tensile break strength, tensile break strain, and stress crack resistance. Because stress cracking is the mode of final failure in the field, the authors consider this to be the most appropriate determinant of end of service life, assuming the data are available. The equations used in predicting the duration of each stage of geomembrane service life considering the idealized liner temperature history are presented herein. A detailed description of these equations is beyond the scope of this paper and can be found in Rowe and Islam (2009). The depletion of antioxidants (Stage A) is evaluated using the following equation (Hsuan and Koerner 1998):

$$OIT_t = OIT_o \exp(-st) \tag{1}$$

where OIT_t = OIT remaining at any time t (min); OIT_o = initial OIT (min); s = antioxidant depletion rate (month^{-1}); and t = time (month). The antioxidant depletion rate at a temperature of interest is evaluated using the Arrhenius equation (Hsuan and Koerner 1998):

$$s = A \exp\left(\frac{-E_a}{RT}\right) \tag{2}$$

where E_a = activation energy (J=mol); R = universal gas constant (8.314 J=mol·K); T = absolute temperature (K); and A = a constant called the collision factor. Eq. (2) can be used directly to predict the antioxidant depletion rate at a constant temperature. To accurately establish Stage B for a given geomembrane and exposure condition, it is necessary to first deplete the antioxidants and determine the initiation of a change in the physical properties of the geomembrane. The Arrhenius parameters for geomembranes during Stage B are not available because laboratory experiments have not been published at more than one elevated temperature (85°C). As a result, the duration of Stage B was calculated using laboratory data at 85°C and an activation energy of 75 kJ=mol, as reported by Viebke et al. (1994) for air-water exposed polyethylene pipe, together with the following equations:

$$\frac{s_{85}}{s_T} = \exp\left(\frac{-E_a}{R}\left(\frac{1}{T_{85}} - \frac{1}{T}\right)\right) \tag{3}$$

$$\xi = \frac{s_{85}}{s_T} \times \xi_{85} \tag{4}$$

where T = temperature of interest (K); T_{85} = 85°C = 358 K; S_T and S_{85} = reaction rates of Stage B at temperatures T and T_{85}, respectively; ξ = Stage B time (years) at temperature T; and ξ_{85} = Stage B (years) at 85°C. Eqs. (3) and (4) are applicable for predicting Stage B at a constant temperature. The calculation procedure for the prediction of Stage C time is the same as that of the Stage B time described previously. Because Stage C Arrhenius parameters are not yet available, the duration of Stage C was calculated using laboratory data at 85°C and an activation energy of 80 kJ=mol as used by Viebke et al. (1994) for air-water exposed polyethylene pipe, together with Eq. (3):

$$\lambda = \frac{s_{85}}{s_T} \times \lambda_{85} \quad (5)$$

Because antioxidant depletion times are not typically calculated for geomembranes installed at MSW facilities in the United States, consideration will be given to a 1.5 mm thick geomembrane (Table 1) for which data are available with respect to Stages A–C of the service life (Rowe and Rimal 2008). The Arrhenius equations cited in Table 1 is used to make predictions of Stage A. The first geomembrane was immersed in simulated MSW leachate (no applied stress). This is the most common aging test reported in the literature (Hsuan and Koerner 1998), but is likely to be overly conservative because it implies the geomembrane is exposed to leachate on both sides. If the geomembrane is located away from holes in a composite landfill liner, the top may be exposed to leachate but the bottom is usually in contact with a LHCSL and not leachate (Rowe 2005). The second aging method in Table 1 reflects the most realistic landfill conditions because it involves a full simulated composite liner [from bottom up: a sand foundation layer, geosynthetic clay liner (GCL), geo-membrane, 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 (Rowe and Rimal 2008).

Table 1. Initial properties and aging conditions of 1.5 mm thick geomembrane (data from Rowe and Islam 2009).

Aging method	Synthetic leachate	Std-OIT (min) [ASTM D3895]	Arrhenius equation	Ea (kJ/mol)
Immersed geomembrane	Surfactant, trace metals, and reducing agent	135	$\ln s = 20.37 - \frac{7304}{T}$	60.7
Simulated composite landfill liner	Surfactant, trace metals, and reducing agent	135	$\ln s = 20.63 - \frac{7703}{T}$	64

To predict the service life of a HDPE geomembrane, it is necessary to assume an idealized temperature variation with time (Figure 3). The temperature at the base of the landfill is assumed to start at T_o (typical ground temperature in the absence of landfilling) and remains constant until a time t_1. The temperature then increases linearly to an intermediate value of T_i (due to waste decomposition) at time t_2 and remains constant until a time t_3. The temperature increases again linearly to a peak value of T_p (due to, e.g., exothermic reaction or smoldering combustion) at time t_4 and remains constant until a time t_5. After time t_5, the temperature decreases linearly and reaches the initial ground temperature T_o at time t_6 and remains constant thereafter. Figure 3 shows the time-temperature history for a landfill experiencing elevated temperatures (Stark et al. 2012; Jafari et al. 2014). In particular, the landfill operated as a dry cell (no leachate recirculation) for the first 5 years. The initial temperature T_o is assumed to start at 20°C and to remain constant for 5 years (time t_1). When the facility began recirculating leachate at time t_1, accelerated waste biodegradation causes temperatures to reach T_i (see 45°C in Figure 3). Koerner et al. (2008) monitored the temperatures on the primary geomembrane on a "wet" cell and measured rapidly increasing temperatures from 20 to 50°C after 5.7 years of landfilling. Therefore, time t_2 corresponds to 5 years after time t_1. Gas wellhead temperatures and thermocouples located in the leachate collection system indicate that elevated temperatures escalated from 45°C (115°F) to 80°C (175°F) in about 0.5 year. Thus, the intermediate temperature T_i remains constant for approximately 4.5 years and the time t_4 to reach T_p is approximately 6 months. The elevated temperatures remain at peak temperature T_p for 5 years before linearly decreasing and finally reaching the initial temperature T_o (20ºC) at a time t_6 (35 years).

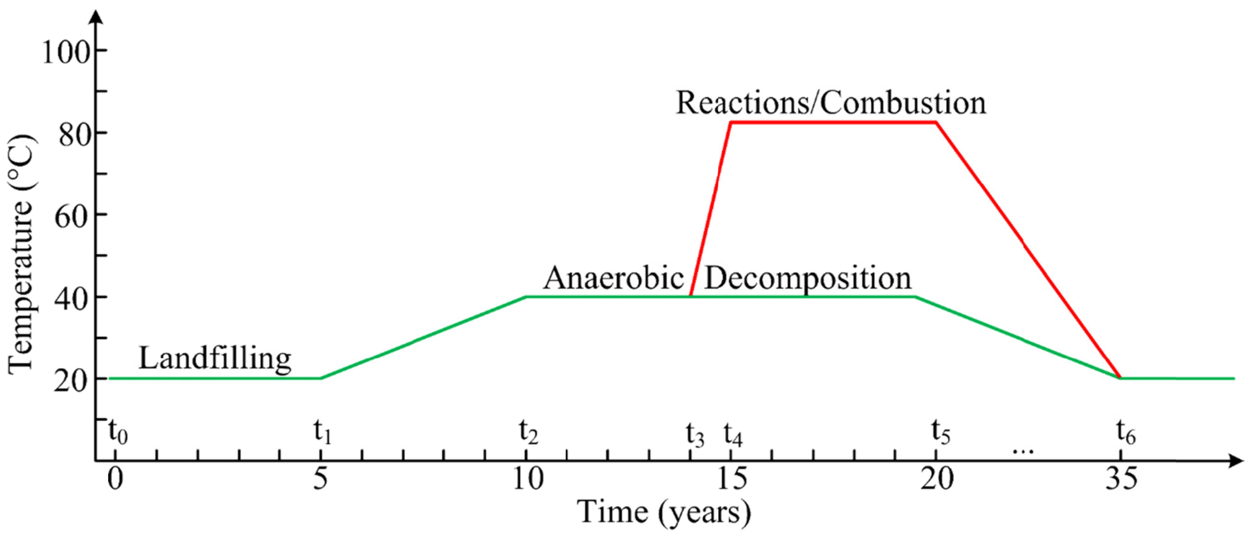

Figure 3. Idealized time-temperature history in a landfill under elevated temperatures.

The estimated times to complete Stages A to C and evaluate the total service life are summarized in Table 2. In cases where the geomembrane was aged by immersion in synthetic leachate, the time to antioxidant depletion (Stage A) is relatively small (13 years) for both anaerobic decomposition and elevated temperatures. For the geomembrane aged in simulated composite liner systems, Stage A varied from 26 to 16 years when temperatures increased from anaerobic decomposition to elevated temperatures, respectively. For anaerobic decomposition, the geomembrane service life is likely adequate because Stage B is completed in 19 years and 120 years, with the former representing the conservative immersion test. Because the liner temperature returns to the original ground temperature by the end of Stage B, Stage C lasts a long time (about 690 years) for both immersion and simulated liner aging conditions. However, the elevated temperature conditions causes substantially shorter geomembrane service life, and the integrity of the geomembrane may be compromised. For example, Stage B is completed in 1 to 2 years for both test setups. The peak temperature of 80°C experienced by the HDPE geomembrane increases the likelihood of failure because Stage C is completed in a short time (about 3 years). The service life of HDPE geomembranes (Table 2) is calculated by adding the durations of Stages A to C. The service life varied from ~17 to 900 years. For elevated temperature situations, the service life of the geomembrane could be reached within the contaminating lifespan.

Table 2. Estimated Stages A-C and service life for time-temperature history.

	Anaerobic Decomposition		Elevated Temperatures	
	Immersion Test	Simulated Liner	Immersion Test	Simulated Liner
Stage A	13	26	13	16
Stage B	19	120	1	2
Stage C	~690	~690	~3	~3
Service Life	~730	~900	~17	~21

DISCUSSION ON SERVICE LIFE

The service life of a geomembrane is considered to have been reached when the properties have degraded to the point where they are no longer sufficient to resist the stresses and strains induced in the geomembrane [e.g., stresses and strains developed because of indentations from the gravel particles in an overlying leachate collection system (Rowe et al. 2009) or because of shear displacements at or near side slopes (Fox and Thielmann 2013)], and the geomembrane develops sufficient fully penetrating cracks (ruptures) to allow an escape of fluids that exceeds the design limits. Thus, the time at which actual failure occurs will depend on the relationship between the resistance of the geomembrane (a function of the polymer [antioxidant package] and the exposure conditions [temperature and leachate]) and the demand (e.g., tensions on slopes, near wrinkles, beneath the drainage gravel, at welds, etc.).

Effect of tensile strains. Because geomembrane coupons (samples) in an immersion test are not under stress (i.e., the demand is zero), they provide information regarding the changes in geomembrane properties with time (i.e., an index for the change in resistance), but they do not necessarily crack/rupture while immersed unstressed. As a result, Ewais et al. (2014) investigated the effect of geomembrane service life (Stages A to and C) when subjected to tensile strains imposed in simulated field conditions and an elevated temperature of 85ºC. They found the service life of geomembranes used in composite liners in MSW landfills depends on the characteristics of the geomembrane, it also will depend on the magnitude of the stresses/strains induced in the geomembrane from the overlaying gravel layer. Thus, the choice of protection layer and the gravel used is important. For example, the geotextile protection used in the study (580 g/m^2) was effective in preventing ductile puncture, but it was not sufficient to protect the geomembrane from stress cracking under sustained local tensions induced by the poorly graded 50-mm crushed limestone gravel at 85ºC. In particular, Ewais et al. (2014) observed brittle ruptures in the geomembrane as a result of excessive tensions at local indentations induced by the overlying coarse gravel in as few as 3 years at 85ºC. This rupturing occurred even though the geomembrane still had a relatively high stress crack resistance (~83% of the initial value) and a relatively high tensile break strength (~92% of the initial value). As a result, Ewais et al. (2014) indicate that to increase the time to rupture of HDPE geomembranes in composite liner configurations under landfill conditions (especially at elevated temperatures), it is important to minimize the local tensions induced in the geomembranes.

Effect of geomembrane thickness. Although immersion tests do not consider the effect of tensile stresses in the geomembrane during aging and expose the geomembrane to the immersion fluid from both sides, they do provide insight regarding the aging of geomembranes and allow a comparison of the relative aging of different geomembranes, e.g., the effect of thickness. In the United States, Subtitle D for nonhazardous waste liner systems requires a minimum thickness of HDPE geomembranes of 1.5 mm to allow proper seam welding (U.S. EPA 1993). In Canada, Ontario regulation 232/98 requires a minimum of 1.5 mm for the primary geomembrane landfill liner and 2.0 mm for the secondary geomembrane landfill liner (Rower 2012). In Europe, the German's require a minimum thickness of 2.5 mm (Federal Institute for Materials Research and Testing 1999). Rowe et al. (2010) tested three commercially available HDPE geomembranes having nominal thicknesses of 1.5, 2.0, and 2.5 mm. The depletion of antioxidants over a 30-month testing period was 30 and 50% longer for the 2.0 mm and 2.5 mm geomembranes, respectively, than for the 1.5-mm geomembrane. This difference was considered to be caused by the longer diffusion path for antioxidants with increasing geomembrane thickness.

Rowe et al. (2014) expanded on these results by extending the testing time in the experiments initiated by Rowe et al. (2010) by almost threefold to seek insight into the effect of geomembrane thickness on the time to nominal failure. The changes in the tensile properties, melt index, and stress crack resistance were examined to define the time of transition from Stage B to Stage C and the time to nominal failure, i.e., when the property of interest drops to 50% of the initial and/or the minimum value specified in GRI-GM13 (GRI 2012). Using 35ºC as the temperature for comparing Stage A to C durations for the three thicknesses, Rowe et al. (2014) report Stage A was predicted to be 16, 19, and 21 years for the 1.5, 2.0, and 2.5 mm geomembranes, respectively. The time to the end of Stage B, when the stress crack resistance was fully retained, was estimated to be 29, 33, and 37 years for the 1.5, 2.0, and 2.5mm geomembranes, respectively. Finally, the time to nominal failure based on the stress crack resistance decreasing to 50% of the initial value was 38, 43, and 65 years for the 1.5, 2.0, and 2.5 mm geomembranes, respectively. Rowe et al. (2014) indicate 2.5 mm geomembrane is likely to have a longer service life than the thinner geomembranes. Furthermore, the tensile strains for the 2.5 mm geomembranes under field conditions is expected to be less than for the thinner geomembranes (other things being equal). Because the demand side (strains) and the resistance side (stress crack resistance) of the 2.5 mm geomembrane are expected to be better than thinner geomembranes, the 2.5 mm HDPE geomembrane can be expected to have a longer service life than the 2.0 and 1.5 mm geomembranes for the three geomembranes they examined. As a result, thicker geomembrane can be one alternative to provide a longer service life, especially for landfills anticipating elevated temperatures, e.g., industrial waste monofills like aluminum production wastes, bottom ash, lime kiln dust, tires, among others. However, a disadvantage of thicker geomembranes is the inherent difficulty to install and seam HDPE geomembranes in the field.

Effect of alkaline leachate. With applications in industrial wastes, such as low-level radioactive waste (LLRW) landfills, aluminum production waste monofills, gold and silver heap leach applications, mining ponds, storage of Bayer process spent residue, and brine ponds, HDPE geomembranes may be exposed to pH values between 9 and 14 (Abdelaal and Rowe 2015). Based on the data cited covering 10 LLRW leachates, Abdelaal and Rowe (2015) indicate LLRW leachates may have a pH ranging from 5.7 to 12.3, with inorganics and radionuclides being the primary contaminants. The service life estimated herein (see Table 2) involved synthetic MSW leachate. However, under more extreme pH conditions, leachate can play an important in the degradation of geomembranes. For example, Abdelaal and Rowe (2015) examined the antioxidant depletion of a geomembrane-immersed high pH leachate (9.5–13.5). Based on Arrhenius modeling of data at five different temperatures (40, 65, 75, 85, and 95°C), the length of Stage A at 30°C was measured to be approximately 43 years for pH 9.5, 39 years for pH 11.5, and 25 years for pH 13.5. The results show that the increase in the pH shortened the length of Stage A based on Std-OIT, which highlights the need to include site-specific leachate characteristics in the estimates of geomembrane service life.

SUMMARY

This paper highlights some of the questions that can arise when assessing the integrity of a composite liner system in the presence of sustained elevated temperatures. The presented idealized time-temperature history shows temperatures at a MSW facility increased from normal operating conditions (45°C) to elevated temperatures (70°C to 85°C) due to APW reactions and smoldering combustion of MSW. When temperatures are in the range of normal MSW landfills, the geomembrane is expected to have a service life of several centuries. When peak temperatures reach 80°C, the geomembrane service life can be reduced to decades for the conditions examined and thus raises concerns regarding the integrity of the geomembrane at high temperatures. Among many factors, the geomembrane thickness, tensile strains induced on the liner from overlying gravel, and leachate pH impact the service life of geomembranes. For example, the combined effect of temperature and tensile strains can initiate stress cracking and rupture the geomembrane. As a result, it is imperative to provide sufficient protection to the geomembrane from gravels in the leachate collection system. Studies show that high pH values play an important role in Stage A antioxidant depletion, while not discussed specifically it is expected that low pH values have a similar effect on service life. Thicker geomembranes can lengthen the service life of geomembranes, but the difficulty in installation may reduce seam quality.

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