



Development of an Apparatus to Simulate the Ageing of Geomembranes under Chemical Exposure, Elevated Temperatures and Applied Stresses

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ABSTRACT

A new apparatus has been developed to obtain improved estimates of the service life of geomembranes when used as part of the barrier system in municipal solid waste landfills. The apparatus, called a geosynthetic liner longevity simulator (GLLS), is a cylindrical steel pressure vessel (600-mm interior diameter, 470-mm high) that is capable of simulating the ageing of geomembranes under chemical exposure, elevated temperatures and applied stresses. The development of the GLLSs is described. Results from prototyping trials of a leachate circulation system to obtain uniform leachate concentrations are presented. The development of the heating system is documented. The physical boundary conditions imposed on the geomembrane are discussed. Preliminary results on the antioxidant depletion and tensile strains of a 1.5-mm thick, high-density polyethylene geomembrane exposed to a synthetic leachate and under 250 kPa of applied pressure are presented.

1. INTRODUCTION

A composite liner system consisting of a geomembrane (GM) overlying either compacted clay or a geosynthetic clay liner (GCL) can be a very effective barrier to contaminant transport from a waste containment facility (e.g., a solid waste landfill). For large landfills, the geomembrane liner may be required to retain contaminants for hundreds of years (Rowe et al., 2004). Whether a geomembrane liner provides adequate long-term environmental protection depends on its service life (i.e. the period over which it will perform its intended design function). The service life of a geomembrane depends on the exposure conditions, which in a landfill may involve adverse chemical exposure, elevated operating temperatures, and potentially large physical stresses.

Even a geomembrane that is properly manufactured, designed and installed may be expected to experience some degradation or ageing over its lifetime. High-density polyethylene (HDPE) geomembranes are most commonly used for landfill barrier systems given their excellent resistance to a wide range of chemicals (Tisinger et al., 1991; Koerner, 1998; Rowe et al., 2004). However, they are susceptible to chemical degradation from oxidation and consequently antioxidants are added to delay the onset of oxidation. The time to complete chemical ageing of an HDPE GM is typically considered (e.g. Viebke et al., 1994) to be the sum of: the time to deplete antioxidants, the induction time to the onset of polymer degradation, and the time for degradation of the polymer to decrease its properties to unacceptable levels.

Antioxidant depletion rates have been examined by Hsuan and Koerner (1998) for a geomembrane with sand saturated with water above, dry sand below, and subject to a vertical stress of 260 kPa (at temperatures of 55-85°C for up to 2 years). Sangam and Rowe (2002) investigated antioxidant depletion rates for unstressed specimens immersed in air, water and synthetic leachate (at 22-85°C) and showed that antioxidant depletion is 2-4 times faster in leachate than in water or air. Islam and Rowe (2007) extended this work to investigate the effects of leachate composition on antioxidant depletion rates and found that the presence of surfactant had the greatest influence on antioxidant depletion as the surfactant changes the wettability of the geomembrane surface, making it easier for antioxidants to leave the geomembrane into the surrounding fluid. Rowe and Rimal (2008) showed the importance of properly simulating field chemical exposure conditions for the geomembrane as the depletion rates with leachate only on the top surface of the geomembrane when overlain by a geotextile or sand were much slower than those for samples when completely immersed in leachate. However, these later studies have been conducted on physically unstressed specimens. The objective of this paper is to detail the development of a new laboratory apparatus to simulate the ageing of geomembranes under chemical exposure, elevated temperatures and applied stresses.

2. GEOSYNTHETIC LINER LONGEVITY SIMULATORS

A cross-section through the new laboratory apparatus—called a Geosynthetic Liner Longevity Simulator, GLLS—is shown in Figure 1. The GLLS is a cylindrical pressure vessel with an internal diameter of 600 mm and height of 470 mm. The body of the GLLS is made from stainless steel. This apparatus was designed to permit the study of: antioxidant depletion under simulated field conditions involving combined chemical exposure, elevated temperatures and applied stresses; the physical response of virgin geomembranes under chemical exposure, elevated temperatures and long time

frames; and the chemical ageing and physical response of the geomembrane following the onset of polymer degradation.

Fifty GLLSs have been developed to permit multiple simultaneous experiments. This was necessary since for one experimental variable the experiments are conducted at a minimum of three different temperatures (85, 70 and 55°C) to obtain accelerated ageing results and identical tests have been scheduled to be terminated at multiple different times to infer the geomembrane properties with time. Also, the GLLS experiments need to run for long periods of time, ranging between 2 months to greater than 2 years. The large number of GLLSs also permits multiple barrier configurations to be examined.

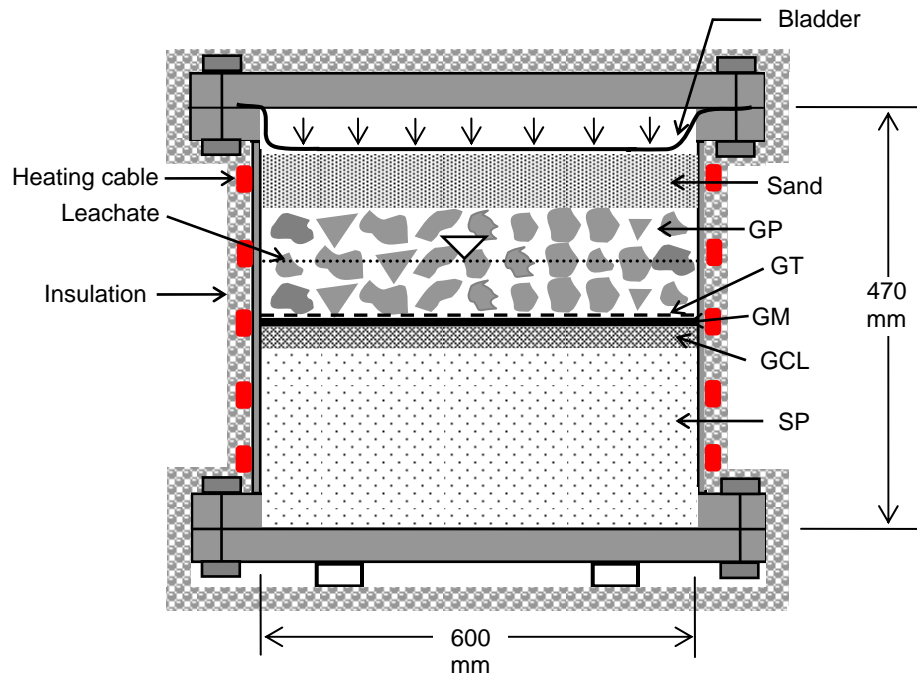


Figure 1. Cross-section through GLLS.

3. CHEMICAL EXPOSURE

3.1 Leachate Composition

At present, only one particular leachate composition is being examined in the GLLSs. It consists of a surfactant (5 mL/L Igepal CA720) and a trace metal solution (see Islam and Rowe 2007) and has a pH of 6. Islam and Rowe (2007) demonstrated that this simple synthetic-leachate produced similar OIT depletion rates compared to more complex leachates involving volatile fatty acids and inorganic nutrients.

3.2 Leachate Refreshing

As antioxidants are depleted from the geomembrane, there is a potential that the concentration of antioxidants in the surrounding fluid will increase. This would change the concentration gradient between the geomembrane and surrounding fluid and thereby reduce the rate of outward diffusion of antioxidants from the geomembrane. Consequently, it was decided to refresh the leachate in the experiments to prevent the build up of antioxidants in the leachate. This essentially provides known leachate properties throughout the experiment, which is important when trying to quantify antioxidant depletion under laboratory controlled conditions. This also simulates the practical situation of where leachate is actively collected above the geomembrane from the overlying collection system. While the leachate in the gravel above the geomembrane will be changed, there may still be a build up of antioxidants in the protection layer; however, since this may also occur under real landfill conditions it was decided to include this factor in the experiments.

The issue of how frequent the leachate should be changed was examined by immersing geomembrane specimens in leachate and varying the time between the leachate replacement. Rowe et al. (2008) found that the antioxidant depletion

rate was slower if leachate was not changed at least every two weeks. Consequently, the new GLLSs were designed to completely refresh the leachate every two weeks.

3.3 Leachate Circulation

It was also decided to continually mix the leachate in the GLLS between the two-week refreshment periods. This was done to avoid areas of stagnant flow in the experiments that could lead to a build up of antioxidants in the leachate. An external leachate circulation loop was developed where fluid is drawn out from one side of the vessel and re-injected into the other side, as shown in Figure 2.

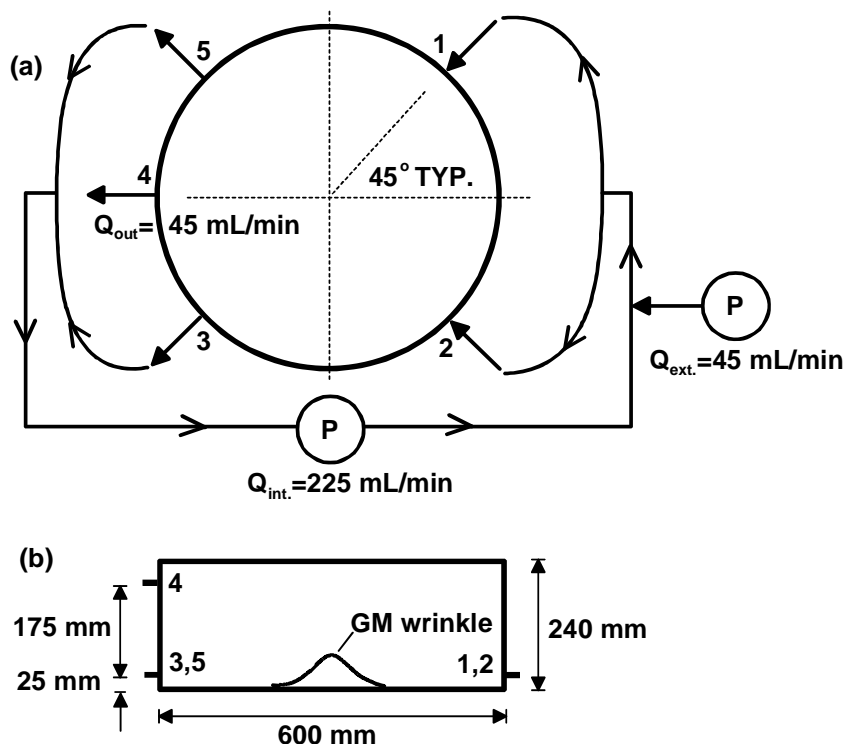


Figure 2. (a) Plan view and (b) elevation view of apparatus and port configurations used in leachate circulation trials.

Achieving uniform mixing of the leachate was complicated by the presence of the wrinkle in the geomembrane. Thus in order to ensure that this fluid was completely mixed and to allow for visual confirmation of the mixing, mixing trials were conducted in an apparatus with transparent sides with a diameter of 600 mm and a height of 240 mm. A geomembrane with a 60-mm-high, 200-mm-wide wrinkle was placed in the bottom of the apparatus. A total of 11 ports were installed in the side of the apparatus so that many inlet/outlet port configurations could be tested – only five are shown in Figure 2. Several dye tests were performed where a constant source of potassium permanganate and water solution was injected at a constant flow rate. Photographs of the top and sides of the apparatus were taken every minute to establish when full mixing was attained. Once full mixing was reached, clean water was injected into the cell until the cell water had cleared to also assess the effectiveness of the circulation loop. The simplest configuration examined consisted of one inlet port at the bottom (located midway between ports 1 and 2 in Figure 2), and one outlet port at the top (shown as port 4 in Figure 2) with the wrinkle located perpendicularly between the two ports. The results from this trial showed that for a circulation flow rate of 45 mL/min, complete mixing of the fluid was not achieved even after 4 hours. A stagnant zone developed beneath the outlet port on the downstream side of the geomembrane wrinkle. The best results were achieved when the circulation loop had a flow rate of 225 mL/min and the port configuration was as shown in Figure 2. For this flow rate and port configuration, full mixing was observed within 30 minutes.

These visual observations of mixing were verified with additional trials where a known concentration of fluorine was injected into the transparent apparatus. The concentrations at nine positions arranged on a 150 mm square grid in the centre of the apparatus and at twelve equally-spaced positions around the perimeter of the apparatus were measured with a fluorometer at the top, middle and bottom of the fluid. The fluorometer was inserted slowly and the tip was wiped

clean after each reading to obtain consistent readings. There were no discernable gradients of fluorine across the geomembrane for the case shown in Figure 2, suggesting that the proposed circulation system provides essentially uniform leachate concentration conditions on the top of the geomembrane.

4. HEATING SYSTEM

The GLLSs have been designed to operate at elevated temperatures of 55, 70 and 85°C to permit the extrapolation of antioxidant depletion rates to lower service temperatures. They also have been designed for 35-55°C to quantify the physical response at temperatures that may be reasonably encountered in a landfill (Rowe, 2005; Koerner and Koerner, 2006).

Leachate is introduced into each GLLS at the particular test temperature having been mixed and preheated in a 650 L stainless steel tank. A heating and insulation system is then required to initially heat the geomembrane and soil materials and then maintain the geomembrane at the test temperature. The heating system consists of heating cables that are wrapped around the perimeter of the body of the GLLS and that are connected to a control system. The GLLSs are also wrapped with insulation to reduce the thermal input required to maintain the test temperature.

Prototyping trials were conducted to select the wattage required for a given insulation system. The task here was to provide enough wattage to maintain the geomembrane temperature within $\pm 1^\circ\text{C}$ of the target test temperature; but not too much wattage so as to reduce the number of on-off cycles experienced by the heating cable to promote a longer cable service life. The service life of the cable is important in this study as some of the GLLSs experiments will run for many years. A self-regulating heating cable that is 13-mm wide and 6-mm thick with a nominal wattage of 66 W/m was selected. However since it is self-regulating (needed for safe long-term operation to avoid local overheating), the wattage of the cable decreases as the temperature increases. Consequently trials had to be conducted for each possible test temperature. These heating trials were also used to the design insulation system. The final design consists of a removable heating jacket with 100-mm-thick fiberglass insulation contained inside a silicone-coated fiberglass cloth.

A schematic of the heating trials is illustrated in Figure 3. A 1.5-mm-thick HDPE geomembrane was placed over the GCL. The GCL was installed at an initial water content of 125-130%. Air-dried poorly-graded sand was used as the foundation layer. Water was circulated through the leachate circulation loop at a flow rate of 225 mL/min. Sixteen thermocouples were used to measure the temperature on the geomembrane (T1-T5), in the soil beneath the geomembrane (T10-T12), above the geomembrane (T7-T9), on the apparatus (T6 and T13), on the external leachate circulation pipes (T15-T16) and on the heating cable (T14).

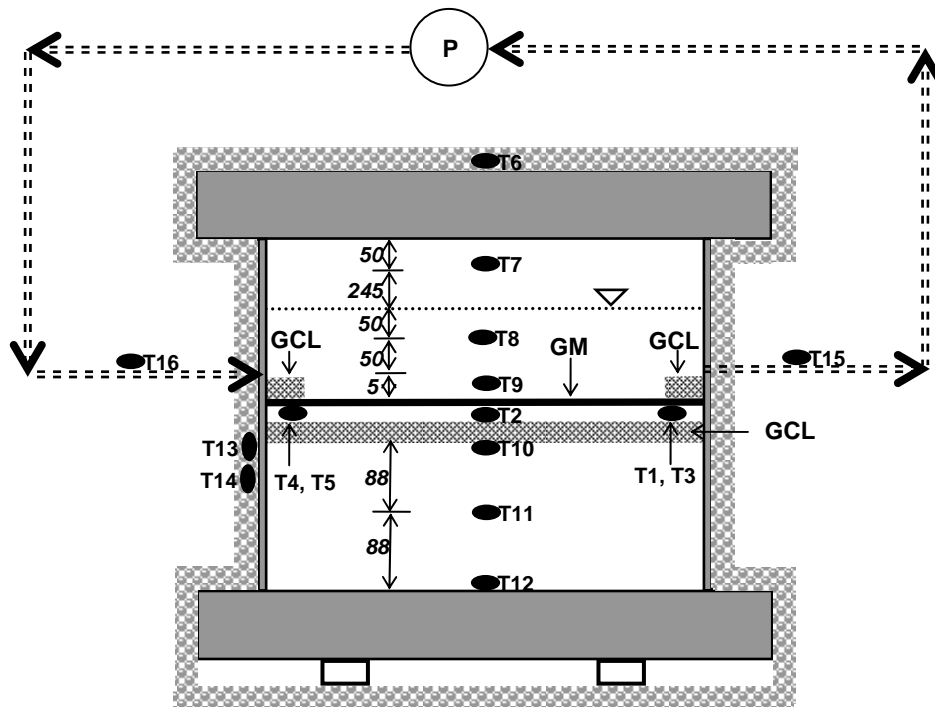


Figure 3. Cross-section through GLLS showing the configurations for the heating trials.

The required length of heating cable to attain a given set-point temperature is summarized in Table 1. The uniformity of temperature within the GLLS was also assessed in these heating trials. Table 2 provides the temperature recorded at the 16 points once steady-state thermal conditions were attained for the particular set-point temperature examined.

Table 1. Required length of self-regulating heating cable.

Geomembrane temperature (°C)	Required length (m)
35	1.8
55	4.3
70	6.1
85	10.7

Once steady-state thermal conditions were reached, the maximum variation in geomembrane temperature at any of the five locations was $\pm 0.1^\circ\text{C}$. The maximum difference between readings on the geomembrane was 1°C for a set-point temperature of 35°C and 2°C for 85°C . This demonstrates that the heating system, insulation and controls of the GLLS are able to provide control of geomembrane temperatures within $\pm 1^\circ\text{C}$.

The vertical temperature gradient across either the geomembrane (T9 and T2) or GCL (T2 and T10) is very small (less than 1°C) for all set-points. There is a thermal gradient through the fluid above the geomembrane. The lower fluid (T9) was 3 to 11°C cooler than the upper fluid (T8) for set-points of 35°C and 85°C . This arises from an overall vertical thermal gradient through the GLLS, with the top warmer than the bottom. This is caused by the insulation on the bottom of the GLLS not being as effective as that at the top, as the bottom required openings for fork-lift slots to permit lifting and moving of the GLLS.

The coolest point was at the base of the GLLS (T12). The thermal gradient through the sand foundation layer increased as the set-point increased, with a difference of 1.8°C at 35°C increasing to 3.4°C at 85°C . Although small, such gradients may actually be a real condition experienced in the field where the warm mass of waste in the landfill sits above cooler surrounding ground. This could lead to moisture movement away from the GCL to the cooler soil beneath (Southen and Rowe, 2005). The temperature at the bottom of the apparatus will be monitored in some long-term GLLS experiments to permit additional study of potential moisture migration.

The heating cable itself experienced a maximum temperature of 120°C ; this information was used to select appropriate materials for the insulation system. The results in Table 2 also show that in addition to heat losses through the insulation, the heating system needs to overcome the heat loss as fluid passes through the external circulation loop. For example, at a set-point of 85°C , the water cooled by up to 8°C between the outlet and inlet ports.

Table 2. Steady-state temperatures ($^\circ\text{C}$) at various locations from the heating trials. Values averaged over 15 minutes.

Location	Set point ($^\circ\text{C}$)			
	35	56	72	85
T1 Geomembrane	35.2	55.9	72.6	84.1
T2 Geomembrane	35.0	55.9	72.1	84.0
T3 Geomembrane	35.0	55.9	72.6	85.0
T4 Geomembrane	34.4	56.1	72.2	83.6
T5 Geomembrane	34.3	56.1	72.4	85.7
T6 Exterior lid	41.0	55.5	83.9	97.3
T7 Airspace	40.6	62.4	83.8	99.7
T8 Upper fluid	38.1	61.7	80.0	95.2
T9 Lower fluid	35.3	56.5	72.5	84.6
T10 Beneath GCL	34.2	54.9	71.3	83.0
T11 Middle of sand	33.3	53.7	70.1	81.3
T12 Bottom of sand	32.4	52.4	68.6	79.6
T13 Exterior body	39.1	62.1	85.7	111
T14 Heating cable	56.8	84.8	92.9	120
T15 Leachate outlet	35.6	56.7	73.2	87.2
T16 Leachate inlet	34.3	54.0	69.4	78.8

5. PHYSICAL BOUNDARY CONDITIONS

The physical boundary conditions of the GLLSs have been selected to simulate the physical conditions expected at the base of a landfill. The top boundary condition simulates the weight of the overlying waste and consists of a uniform vertical pressure applied by air pressure to a flexible rubber membrane. The membrane is anchored between the lid and upper flange of the body of the GLLS. The GLLSs have been designed for a maximum working pressure of 1000 kPa. The boundary condition along the walls of the GLLS was designed to provide essentially zero lateral displacement under 1000 kPa of vertical pressure. This enables horizontal stresses in the gravel above the geomembrane and the sand below the GCL to develop for each material for zero lateral strain (i.e. K_0) conditions. The potential for friction to be mobilized along the walls is minimized by using layers of thin polyethylene sheets lubricated with high-temperature bearing grease. This has been shown to reduce the friction along the interface to less than 5° (Tognon et al., 1999). Brachman and Gudina (2002) have shown that for the dimensions of the GLLS and with boundary friction of 5°, greater than 95% of the applied stresses reach the geomembrane.

6. PRELIMINARY RESULTS

6.1 Antioxidant Depletion

One suite of GLLS experiments is intended to quantify the depletion of antioxidants in the geomembrane under realistic exposure conditions. These experiments have leachate exposure only on the top of the geomembrane and not necessarily across the entire top surface depending on the gravel contacts and protection layer. Because of the difference in exposure conditions, these GLLS experiments will take longer to complete than specimens simply immersed in leachate. It is anticipated that these experiments could run up to 2 years. Consequently, to permit study of geomembrane ageing beyond the depletion of antioxidants (i.e. the subsequent polymer degradation) another suite of experiments are being conducted on geomembrane specimens that have been pre-aged at elevated temperatures. A large (700 L) insulated stainless steel immersion tank was developed to pre-age up to sixty 0.76-m-square geomembrane specimens at $85 \pm 3^\circ\text{C}$. The depletion of antioxidants, expressed in terms of the oxidative induction time (OIT), in 1.5, 2 and 2.5-mm-thick HDPE geomembranes from the immersion tank are plotted in Figure 4. These values were obtained from Standard OIT tests (ASTM D3895) conducted using a TA Instruments Q-100 series differential scanning calorimeter. Nearly five months of ageing at 85°C was required to deplete most of the antioxidants (OIT < 1 minute) for the 1.5-mm-thick geomembrane. It is taking a little longer for the thicker (2.0 and 2.5-mm-thick) geomembranes which have been reduced to OIT values less than 3 and 5 minutes, respectively after 5 months. This slower depletion rate with increasing thickness is consistent with the findings of Islam and Rowe (2007). Most of these specimens will continue to be aged in the immersion tank until the end of stage II of the service life (onset of polymer degradation), while some have been removed to quantify the time to reach the onset of polymer degradation in the GLLSs.

6.2 Geomembrane Strains

The GLLSs are also being used to quantify the physical response of the geomembrane under simulated field exposure conditions. Preliminary results on the influence of temperature on the strains that develop in the geomembrane are presented here. From the top-down, the particular configuration tested (shown in Figure 1) involved: nominal 50-mm coarse gravel to simulate the leachate collection system, a nonwoven needle-punched geotextile (4.1-mm-thick, with a mass per unit area of 570 g/m^2) as the protection layer, a virgin 1.5-mm-thick HDPE geomembrane placed without a wrinkle, a GCL (having slit-film carrier and nonwoven cover geotextiles, and with initial water contents between 125-130%) and a firm sand foundation layer. Vertical pressure was applied in 50 kPa increments every 10 minutes to a maximum of 250 kPa that was held for 10 hours. The strains were calculated from measured permanent indentations in a thin lead sheet placed between the geomembrane and GCL using the technique developed by Tognon et al. (2000).

The results are given in Table 3 and show an increase in the maximum geomembrane tensile strain from each test as the temperature increases. This is attributed to decreases in the stiffness of the protection geotextile and geomembrane with increases in temperature.

The strains exceed the proposed tensile limit of 3% of Seeger and Müller (2003), even at 20°C , for the particular coarse gravel and pressure tested. Consequently, the particular geotextile tested should not be relied upon to limit strains in the geomembrane. A 150-mm thick sand protection layer (Dickinson and Brachman, 2006) has been shown to limit the tensile strains to less than 1%. Additional GLLS experiments are currently underway to quantify the long-term physical performance of the geomembrane, GCL and geosynthetic protection layers.

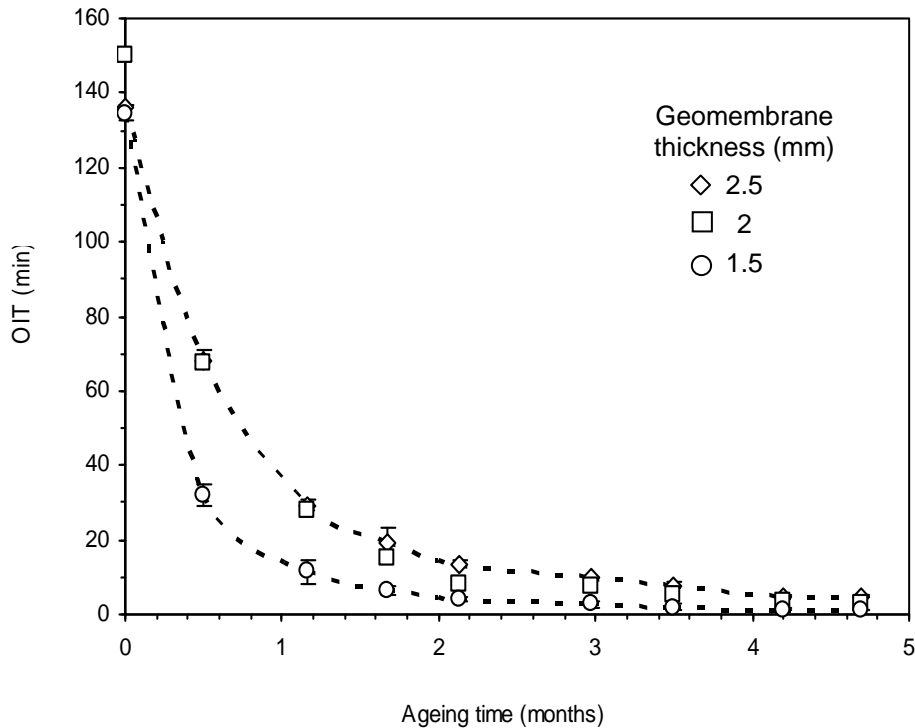


Figure 4. Decrease in oxidative induction time (OIT) with time from large immersion tank.

Table 3. Maximum calculated geomembrane tensile strain at 250 kPa held for 10 hours.

Temperature (°C)	Calculated geomembrane strain (%)
20	11
35	14
55	15
70	16
85	20

7. CONCLUSIONS

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 was described. Results from prototyping trials of a leachate circulation system show that replacing the leachate every two weeks and continuous mixing at a rate of 225 mL/min through two inlet and two outlet ports will provide uniform leachate concentrations. The results from heating trials show that the heating and insulation systems developed are able to provide control of geomembrane temperatures within $\pm 1^\circ\text{C}$. Antioxidant depletion rates of 0.76-m-square geomembrane specimens immersed in a synthetic leachate at $85\pm 3^\circ\text{C}$ to pre-age test specimens for the GLLSs were reported. Nearly five months of ageing at 85°C was required to deplete most of the antioxidants (OIT < 1 minute) for the 1.5-mm-thick HDPE geomembrane tested. Preliminary results from GLLS experiments have quantified the increase in geomembrane tensile strain with increases in temperature. Greater tensions are attributed to decreases in the stiffness of the protection geotextile and geomembrane with increases in temperature. Experiments are currently underway to provide improved estimates of the service life of geomembranes when used as part of the barrier system in municipal solid waste landfills.

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