Effect of liner temperature on the long term stress cracking of HDPE geomembranes under simulated field conditions

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ABSTRACT: The susceptibility of a high density polyethylene geomembrane to long-term stress cracking is investigated under field conditions simulating municipal solid waste landfills. Experiments are conducted in the large-scale geosynthetic landfill liner longevity simulators (GLLS) in which the 0.6 m diameter pre-aged geomembrane sample is underlying a gravel drainage layer and a geotextile protection layer and overlying a geosynthetic clay liner GCL layer. The composite liner configuration is tested under 250 kPa vertical pressure and at a range of temperatures between 40 and 85ºC. The results reported by Abdelaal et al. (2014) showed that, at temperatures between 55 and 85ºC, the geomembrane failure times (due to brittle stress cracking) followed an Arrhenius relation. However, at 40ºC, the geomembrane sample had remained intact for 20 months. The objective of this paper is to present an update to the failure times of the geomembrane liner after four years of testing in the GLLSs. The current results show that the GMB at 40ºC is still intact after further 28 months of testing under simulated field conditions. The current duration of the 40ºC test substantially exceeds the failure time extrapolated from the Arrhenius relation established based on temperatures between 55 and 85ºC suggesting a change in the behaviour of the GMB at lower temperatures below 55ºC.

Keywords: (Geosynthetics, Stress cracking, Geomembranes, Service life, brittle ruptures, long-term performance)

1 INTRODUCTION

As part of the composite liner systems, the role of the polymeric geomembrane (GMB) liner is to safeguard against the leakage of fluids containing the contaminants from source waste to the surrounding environment in lined waste containment facilities. Consequently, the service life of the GMB liner is reached when it ceases to perform this hydraulic barrier role due to excessive leakage through holes in the GMB. In short-term, ductile ruptures can develop in the GMB due to improper construction quality control and/or improper protection form short-term punctures and hence jeopardizing the GMB hydraulic barrier role. In long-term, brittle ruptures in the GMB can develop after waste placement due to stress cracking that is related to the magnitude of the sustained tensile stresses/strains in the GMB following installation. This mode of failure can take place when tensile strains/stresses in the GMB are sustained well below its short-term yield strength for long periods of time. This is because, with time, the GMB experiences degradation and thus a decrease in its resistance/strength than its short-term mechanical strength.

According to Hsuan and Koerner (1998), high density polyethylene (HDPE) GMBs encounter three stages of degradation until the nominal failure in a selected engineering property is reached. This degradation takes place in isolation of the applied field stresses, and hence is usually examined using immersion tests. The degradation stages of the GMB start in Stage I by losing the antioxidants and stabilizers in the GMB then passes through an induction time (Stage II) before the GMB starts to exhibit a decrease in its physical and mechanicals properties with time in Stage III until nominal failure that is characterized by 50% loss in a selected engineering property.

To evaluate susceptibility of HDPE GMB to long-term stress cracking, simulation of the GMB liner field conditions including both the chemical exposure and applied stresses is required. In geosynthetic liner longevity simulators (GLLSs; Brachman et. al 2008), large scale experiments are conducted on the GMBs as part of a composite liner under simulated field conditions including chemical exposure to leachate, elevated temperatures, and over burden pressure using the same materials used in the field (Rowe et al. 2013; Abdelaal et al. 2014; Ewais et al. 2014).

Abdelaal et al. (2014), tested a HDPE GMB, that had been pre-aged in leachate at 85^{o}C to lower its notched constant tensile load (NCTL) SCR (appendix of ASTM D 5397) to 75 hours, as part of composite liner configuration in specially developed GLLS experiments at 40, 55, 65, 70, 75 and 85^{o}C. While the tested HDPE GMB ruptured due to stress cracking mechanism in experiments running at temperatures between 55 and 85^{o}C, the GMB specimens tested in GLLS at 40^{o}C did not rupture after 20 months of testing in the GLLS. This time exceeded the predicted failure time by Arrhenius modelling based on data at 55–85^{o}C, suggesting that behaviour might have changed below 55^{o}C. The objective of this paper is to present a 4-year update on 40^{o}C test to further examine the effect of the GMB temperature on its time to rupture in composite liner configuration under simulated conditions.

2 EPERIMENTAL INVESTIGATION

2.1 *Tested GMB*

The tested GMB is a 1.5 mm thick commercially available HDPE manufactured in 2005 using Pétromont (S-7000) resin. High performance liquid chromatography indicated the presence of hindered phenols (primary) and phosphites (secondary) antioxidants. No hindered amine light stabilizers (HALS) were detected. Table 1 shows the initial GMB properties that met the GRI-GM13 (2016) minimum requirements.

Table 1. Initial properties of the 1.5 mm thick smooth geomembrane examined.

Properties	Test Method	Values (Mean ± SD)	GRI-GM13(2016) minimum values	Meeting the GRI requirements?
Standard oxidative induction time (min)	ASTM D 3895	115 ± 1.5	100 Or 400	Yes since it met one of the 2 OIT requirements*
High-pressure oxidative induction time (min)	ASTM D 5885	260 ± 10		
Melt index (190^{o}C/21.6 kg) (g/10min)	ASTM D 1238	15.9 ± 0.3	1.0	Yes
Single point stress crack resistance (hours)	ASTM D 5397	720 ± 130	500	Yes
Machine direction break strength (kN/m)	ASTM D 6693 (Type IV)	47.3 ± 1.8	40	Yes
Machine direction break strain (%)		822 ± 30	700	Yes
Cross machine direction break strength (kN/m)		46.7 ± 1.8	40	Yes
Cross machine direction break strain (%)		874 ± 46	700	Yes

* Also meets the Oven Aging at 85°C requirement.

2.2 *Preaging method*

To investigate the stress cracking of the GMB under simulated field conditions in a reasonable testing time, the current study involved pre-ageing the GMBs sheets by immersion in a simulated municipal solid waste (MSW) leachate at 85^{o}C for 45 months to reduce the NCTL-SCR to about 75 hours (i.e., 15% of the minimum specified SCR value by GRI-GM13). This step was done prior to installing the GMB in the GLLSs as reported by Abdelaal et al. (2014). Figure 1 summarizes the steps involved in the pre-ageing process. Virgin sheets of 80x80 cm in size were cut to allow sufficient sample for the GLLS tests and then immersed in synthetic municipal solid waste (MSW) leachate in a 1 m^3 stainless steel tank at 85^{o}C to accelerate pre-ageing stage. At different time intervals, samples were cut from the GMB sheets to monitor the change in the index properties with time (Figure 2). After the NCTL SCR of the GMB was reduced to 75 hours, the GMBs were removed from the ageing bath and tested in the GLLS.

The reported degradation of the tested GMB by Abdelaal et al. (2014) showed a Stage I duration of about 4.5 months using both standard OIT (Std-OIT; ASTM D 3895) and high pressure OIT (HP-OIT; ASTM D 5885). Following the OIT depletion, the GMB retained its SCR and other properties for additional 4 months (Stage II duration) then SCR started to decrease signaling the initiation of the degradation stage (Stage III). SCR further decreased to reach 50% of the initial value ($0.5\text{x}SCR_o$ = 360 hours) after about 20 months of incubation and hence Stage III duration was 11.5 months. The degradation in SCR of the GMB commenced with further incubation until reached 75 hours after 45 months.

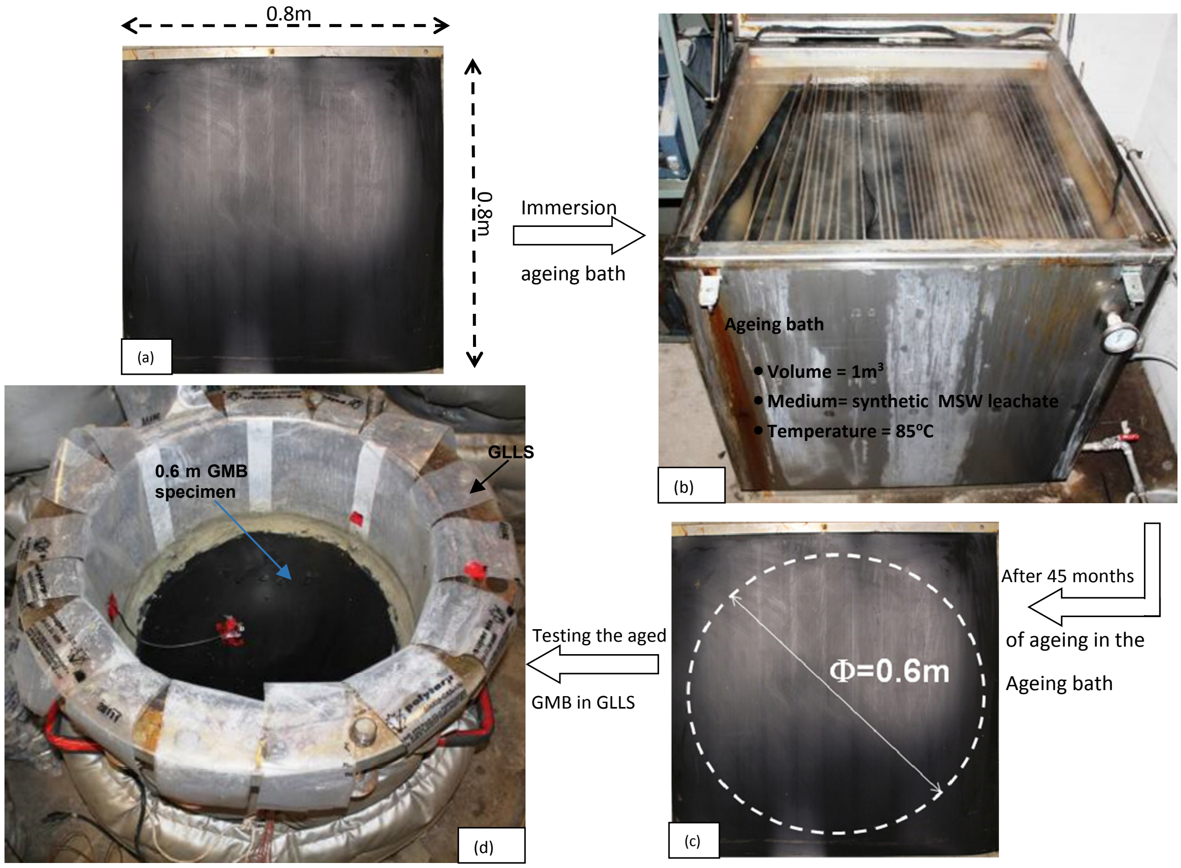

Figure 1. Pre-ageing process involving (a) sheets of virgin GMBs 80x80 cm; (b) immersion of the sheets into ageing baths in MSW leachate at 85°C for 45 months; (c) after ageing and reaching the desired SCR; (d) testing aged GMB in GLLS under simulated landfill liner configurations.

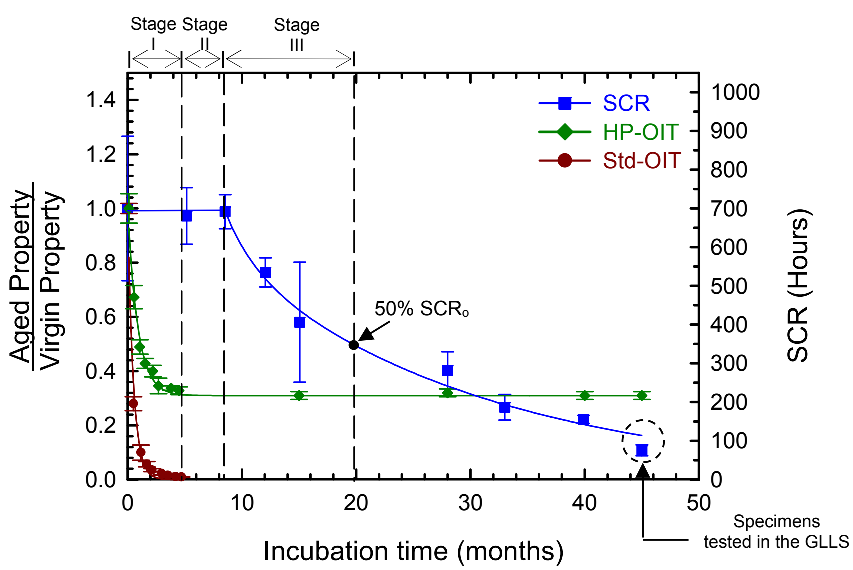

Figure 2. Change in properties with time for the tested GMB immersed in leachate at 85°C.

2.3 *GLLS experiments*

The GLLS configuration examined in Abdelaal et al. (2014) involved the 1.5 mm HDPE GMB samples (Table 1) underlain by a hydrated geosynthetic clay liner (GCL) and overlain by a nonwoven geotextile protection layer (mass per unit area = 560 g/m^2) and poorly graded 50 mm crushed limestone as the drainage layer (Figure 3). Experiments were conducted under 250 kPa and at 40, 55, 65, 70, 75 and 85^{o}C. The GLLS cells were equipped with a leak detection sensor to allow the identification of the time at which a hydraulically significant crack had formed in the GMB in each experiment without opening or temporary terminating the test. Further details on the experimental setup are presented in Abdelaal et al. (2014).

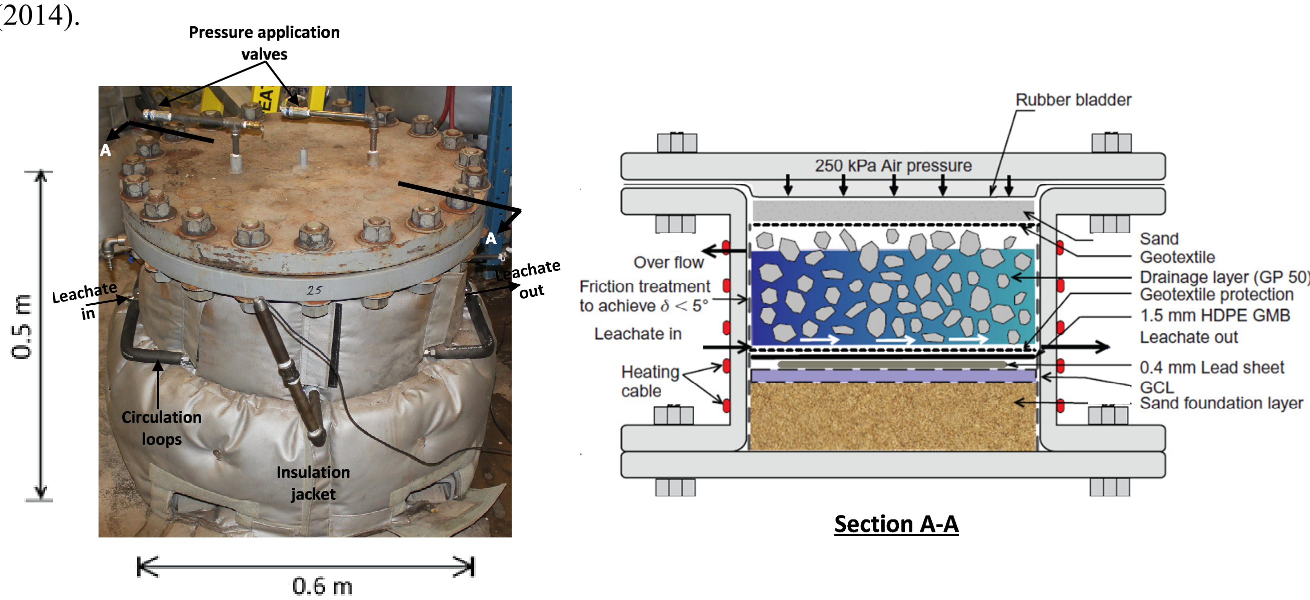

Figure 3. GLLS test Apparatus (modified from Abdelaal et al. 2014).

3 RESULTS AND DISCUSSION

Abdelaal et al. (2014) showed that for GLLS experiments running at temperatures between 55 and 85^{o}C, the rupture time for the GMB specimens was reached after 38 days and 1 day, respectively (Table 2). At this stage, the 40^{o}C was still running for almost 20 months without any indication from the leak sensor of cracks. After running for substantially longer time beyond the time reported in Abdelaal et al. (2014), it was decided to pause the experiment at 40^{o}C and visually inspect the GMB specimen. This inspection was done to ensure that there were no minor cracks initiated in the GMB that were not captured by the leak sensor and to verify that the drainage layer particles did not suffer any deterioration into finer particles.

Table 2. Failure time of GMB pre-aged GMB in GLLS test (55-85^{o}C data are from Abdelaal et al. 2014).

Temperature (^{o}C)	Failure time (hours*)
85	24
75	87
70	100
65	240
55	770
40	>34,560 (4 years)

* Time from application of temperature and pressure in the GLLS until cracks were detected by the leak sensor.

The GLLS experiment at 40^{o}C was paused using the technique described by Abdelaal (2013) with removing the drainage layer to inspect the GMB and then placing the particles exactly back in their original locations so that the indentation shapes and the tensile strains developed in the GMB prior to pausing the test do not change. Figure 4 shows the photograph of the GMB from the 40ºC experiment. The gravel particles overlaying the geotextile protection and in contact with the GMB specimens (Figure 4b) are still maintaining their original size of approximately 50 mm similar to the particle sizes used for other GLLS experiments at higher temperatures. This verifies that gravel used in this experiment did not suffer deterioration (even those directly in contact with the geotextile just above the GMB specimen) that could have affected the test results.

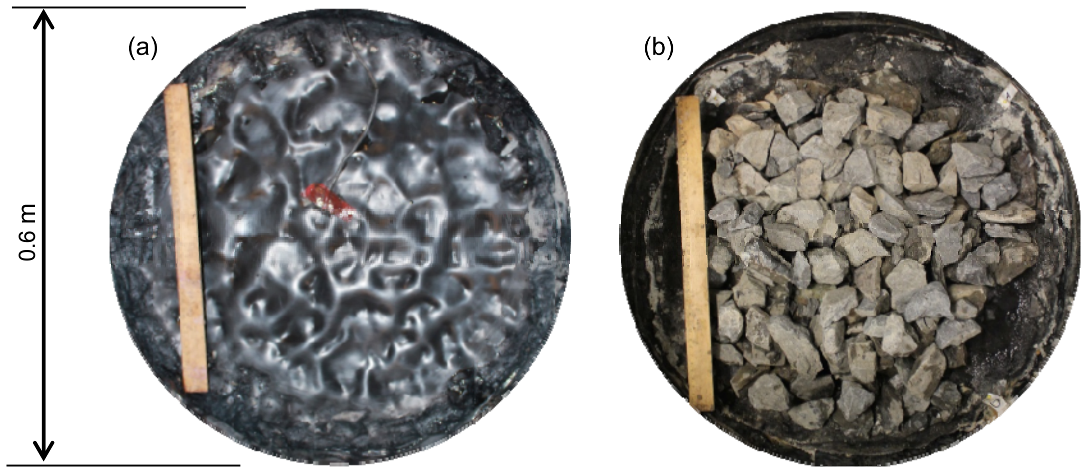

Figure 4. GMB specimens (0.6 m in diameter) from 40ºC GLLS experiments after 4 years of testing showing a) intact GMB specimens; b) drainage layer in contact with the GMB in the GLLS. Scale is 40 cm in length.

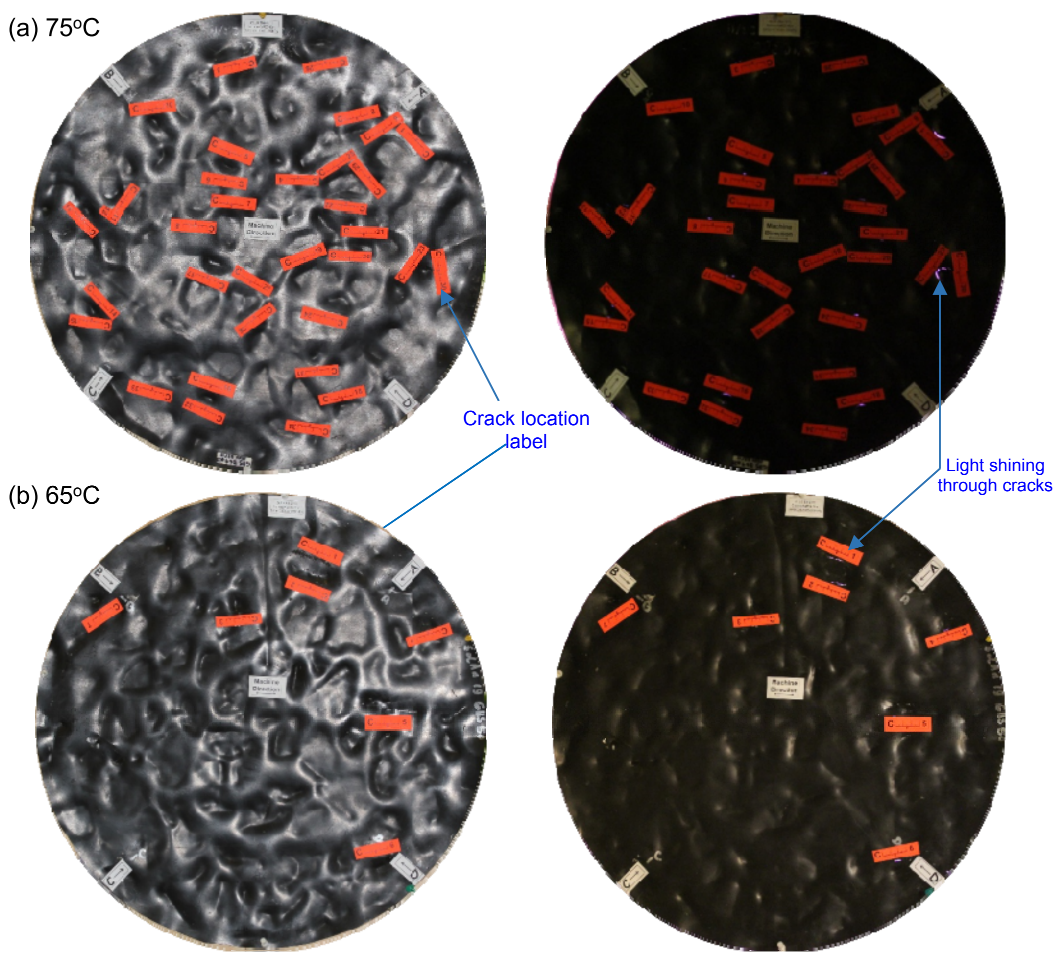

Figure 5. GMB specimens (0.6 m in diameter) after termination of GLLS experiments showing crack locations (marked with red labels) and light shining through some of the larger cracks (fine white lines in the right photograph) at (a) 75ºC; (b) 65ºC.

Figure 4a shows the GMB specimens from the 40ºC GLLS experiment after 4 years with the indentations from the drainage layer after the complete removal of the geotextile protection layer and the overlaying drainage layer. The GMB specimen was visually inspected and showed no signs of rupture in the GMB at any indentation after the 4 years of testing in GLLS under 250 kPa confirming indications obtained from the leak sensor so far. Comparing the depths and sizes of the indentations developed in the 40ºC test to those developed in the ruptured GMB from higher temperature GLLS experiments (75ºC Figure 5a and 65ºC Figure 5b) shows that some of the indentions at 40ºC were as deep and large as those developed in the GMB at 75 and 65ºC GLLS experiments. This suggests that the tensile strains reached after 4 years of testing at 40ºC could be close to those developed in the GMB at the time of rupture at higher temperature experiments (e.g. after about 4 days at 75ºC). Thus, even at similar tensile strains, the current results from 40ºC test highlights the significant effect of temperature on the resistance of the GMB to crack formation under simulated field testing conditions presented herein, i.e., 1 day at 85ºC versus longer than 4 years at 40ºC for the same GMB.

Figure 6 updates the failure time versus temperature plot (Arrhenius format) presented by Abdelaal et al. (2014) with the current running time of the 40ºC experiment. The experimental data obtained at 55, 65, 70, 75 and 85ºC followed a linear relationship when plotted as $\ln(1/F_t)$ versus 1/T suggesting that the nature of the relationship between rupture of the GMB and temperature did not change over these test temperatures (Abdelaal et al. 2014). Using the Arrhenius relation presented in Figure 6 for temperatures between 55 and 85ºC, the prediction of failure time at 40ºC varied between 4 to 16 months based on the 95% confidence limits activation energies. However, the current reported time for the 40ºC (i.e., 48 months) is 3 times the maximum predicted time obtained using the 95% confidence limits activation energies and confirms that the failure at 40ºC did not occur at a time consistent with the failures at higher temperatures. This implies that the slope of the Arrhenius plot for the data below 55ºC shall change due to the possible change in the stress crack behaviour of the GMB for the tested conditions. If this is the case, the rupture times at lower field temperatures (below 55ºC) predicted from the high temperature experiments will likely be conservative (i.e., they err by predicting shorter rupture times).

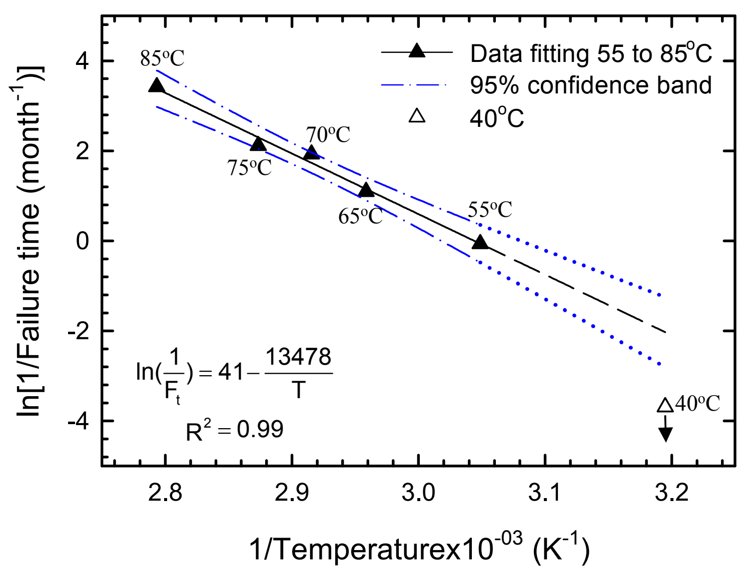

Figure 6. Variation of natural logarithmic of $1/F_t$ versus 1/temperature in Kelvin (Arrhenius plot) (modified from Abdelaal et al. 2014).

4 CONCLUSIONS

This paper presented an update on the rupture time of the GMB in the 40ºC GLLS experiment reported by Abdelaal et al. (2014). The GLLS experiment involved a HDPE GMB pre-aged to SCR= 75 hours by immersion in synthetic leachate for 45 months at 85ºC that was then tested in the GLLS under simulated field conditions including overburden pressure of 250 kPa for 20 months without failure. In this study the 40ºC test was maintained running under the initial boundary conditions for further 28 months (i.e., total of 4 years in the GLLS) and then paused to inspect the GMB specimen and testing conditions. The findings of this visual inspection were:

- No signs of full penetration ruptures in the GMB specimen were seen after 4 years of testing at 40ºC.
- The drainage layer overlaying the geotextile protection layer did not show any signs of deterioration confirming that particles size used to construct the 40ºC cell did not change during the 4 years of testing and was similar to those used for the high temperature experiments.
- The sizes and depths of the GMB indentations due to the gravel contact seemed comparable to those obtained at higher temperature experiments with ruptured GMBs implying that the tensile strains in the GMB at the 40ºC were not lower than those developed in the failed specimens at higher temperatures. This suggests that the delay in rupture time at the 40ºC was mainly due to the substantial increase in the GMB resistance to crack initiation and/or propagation and not due to a significant decrease in the tensile strains in the GMB.

This study highlights the effect of liner temperature on the GMB failure due to stress cracking and hence its service life. For the presented test conditions, the stress cracking behaviour of the GMB specimens changed (for the better) below 55ºC. Furthermore, predications based on the temperatures of 55–85ºC were conservative (i.e. shorter than the actual failure time below 55ºC) indicating the need to change the Arrhenius plot slope for data below 55ºC to account for such change in the GMB behaviour.

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