Stress Crack-Resistance of Textured Geomembrane

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ABSTRACT
The longevity of textured geomembranes (GMB) widely used as base and slope liners is rarely studied. The variability of the thickness and defects on the surface of co-extruded textured GMBs result in non-uniform mechanical properties across the GMB roll. Therefore, the effect of texturing on the stress crack resistance (SCR) of unaged and aged high density polyethylene geomembranes is studied herein. The fracture plane of broken geomembrane specimens in notched constant tensile load (NCTL) test is investigated using the environmental scanning electron microscope. The comparison between the crack growth rate estimated by fracture mechanics laws and the SCR estimated in NCTL test shows that the defects and discontinuities on the textured geomembrane surface are the main source of variability of the NCTL results.
Keywords: Geosynthetics, Geomembranes, HDPE, Textured, Stress crack resistance.

1. INTRODUCTION

Textured geomembranes (GMBs) are used on side slopes and as base liners due to the higher interface shear strength between the GMB and soil/geosynthetics in contact compared to smooth GMBs (Müller 2007; Scheirs 2009; Koerner 2012). Texturing of GMB's surface is beneficial during construction and when there is potential for sliding at the interface during landfilling. Texturing the GMB's surface helps increase veneer stability of the lining system on side slopes (Morsy and Rowe 2020). In service, using textured GMB increases the factor of safety against downslope sliding with degradation and consolidation of the waste, although care is also needed not to induce tensions in the GMB (Rowe and Yu 2019).

Different techniques for texturing the surface of a GMB are: (a) lamination, (b) impingement, (c) structuring, and (d) co-extrusion using inert blowing agent (Stark et al. 1996; Hebeler et al. 2005; Müller 2007; Scheirs 2009). The most common technique in North America and Asia is the co-extrusion using an inert gas (usually nitrogen) and is the one examined in this paper. This texturing technique results in non-uniform core thickness of the GMB and hence, variability in the mechanical properties such as tensile break properties and stress crack-resistance (SCR) across the GMB roll. Morsy and Rowe (2020) estimated the SCR of a textured GMB and its equivalent smooth edge using the notched constant tensile load (NCTL) test and reported that the time to nominal failure of both the textured and smooth portions of the GMB was almost the same, but a large variability in the SCR of the textured portion was observed. The authors attributed this variability to defects and/or discontinuities on the GMB surface, and variability in the thickness/stresses across the specimen. Another factor that could contribute to the variability of SCR results is the variable ligament thickness of notched specimens in the NCTL test (as will be discussed in Section 2.3), and this could be investigated using the fracture mechanics principle (stress intensity factor K_I). Therefore, the objective of this paper is to investigate the different factors that might affect the SCR of unaged/aged textured GMB in the NCTL test and indicate which factor is likely to be a major contributor to the variability of the SCR for these co-extruded GMB.

2. EXPERIMENTAL INVESTIGATION

2.1 GMB Examined

The GMB examined is double-sided textured with 200 mm smooth edge, black, high density polyethylene (HDPE) GMB manufactured in 2015 was produced using co-extrusion with a blowing agent (initial properties; Table 1). This GMB was produced from medium density polyethylene polymer resin and adding 2.5% carbon black raised the density to the range of HDPE (≥0.941 g/cm^3; ASTM D883). The average core thickness of the GMB was 1.5 mm and the average asperity height was 0.43 mm.

2.2 Accelerated Ageing and Incubation Media

Accelerating ageing of the GMB was performed by immersing coupons (9.5×19 cm) in 4-liter glass jars filled with synthetic municipal solid waste (MSW) leachate, and incubated in forced air ovens at 85ºC. The GMB coupons were separated by 5 mm glass rods to ensure the exposure of the GMB to the MSW leachate from both sides. The MSW leachate was composed of DI water mixed with industrial surfactant, trace metal solution, and inorganic/organic salts (TDS~12000 mg/l; Rowe et al. 2008). The pH of the leachate was adjusted in the range of 6.9-7.2 using 15 mol/l sodium hydroxide.

2.3 Notched Constant Tensile Load Test

In the NCTL test (ASTM D5397), a smooth GMB specimen is notched by a sharp razor leaving a ligament thickness equals 80% of the average nominal thickness of the specimen, then placed in a bath filled with an environmental reagent (90% water and 10% surfactant) at 50ºC and loaded by a test load equivalent to a stress equal to 30% the yield strength of the GMB. GRI-GM13 (2016) does not recommend testing textured GMBs using the NCTL method (ASTM D5397). However, Morsy and Rowe (2020) performed this test to compare the time to nominal failure of both the textured and smooth portions of the same GMB examined in the current study. The authors adopted an empirical approach to both notching and approval of specimens suitable for the NCTL test based on multiple experimental observations. The notching machine was adjusted to notch the textured specimen assuming an average thickness of 1.5 mm (60 mil; the thickness of the smooth edge) aiming to achieve a ligament thickness of 1.2 mm (48 mil). However, actually achieving a uniform target ligament thickness for all specimens is challenging due to the variable textured core thickness. In recognition of this practical reality, a specimen was approved for testing if: a) the ligament thickness was not less than 1.0 mm (40 mil; 67% of the ligament thickness), and b) the variation in the ligament thickness did not exceed 4% when measured on both sides of the GMB under the microscope. To count for the variable ligament thickness, the applied test load was adjusted to ensure a stress equivalent to 30% of the yield strength was applied to the tested specimen based on the minimum ligament thickness measured on both sides of the specimen. The SCR of the textured portion of the GMB roll was much more variable than for the smooth edge as implied by the range of SCR for the unaged textured (150-5700 hours) and smooth (2700-5700 hours) portions of the GMB.

Table 1. Initial properties of the GMB examined.

Property	Method	GMB	
Surface condition	--	Textured	Smooth edge
Type	--	HDPE	HDPE
GMB density[1] (g/cc)	ASTM D1505	0.947	0.947
Thickness[1] (mm)	--	1.5 (ASTM D5994)	1.5(ASTM D5199)
Asperity height[1] (mm)	ASTM D7466	0.43	--
SCR (hours)	ASTM D5397	1600(150-5700) [2]	4000 (2700-5700) [2]

[1]Provided by the manufacturer; [2] (minimum-maximum) SCR readings

3. RESULTS AND DISCUSSIONS

3.1. Comparison between the Stress Intensity Factor and NCTL test results

The large variability of the SCR results for the textured geomembrane reported by Morsy and Rowe (2020) was attributed to: (a) unavoidable variability in thickness and stress across the specimens, and (b) defects and/or discontinuities on the textured GMB surface beneath the ligament under the notch. Another factor considered in the current study was the variable ligament thickness of notched specimens and its effect was investigated using fracture mechanics (stress intensity factor K_I). The ligament thickness was variable for the notched aged SCR specimens due to the irregular core thickness of the co-extruded textured GMB.

The stress intensity factor for a finite plate (with an edge crack) and subjected to uniaxial tensile stresses (Figure 1) may be estimated from (Liu et al. 2015):

$$K_I = \sigma \times \sqrt{\pi a} \times \left[1.122 - 0.231(^a/_w) + 10.56(^a/_w)^2 - 21.74(^a/_w)^3 + 30.42(^a/_w)^4\right] \quad [1]$$

where, K_I (kPa.m$^{0.5}$) = stress intensity factor; σ (kN/m) = applied tensile load in the NCTL test; a (m)= crack length; and w (m)= thickness of the specimen.

According to Paris-Erdogan law (Paris and Erdogan 1969), the crack growth rate (*da/dt*) is function in the stress intensity factor (K_I) and other material, temperature, and loading conditions dependent constants (*A* and *m*), and can be estimated from:

$$ {da}/{dt} = AK_i^{m} \qquad [2] $$

Therefore, the crack propagation rate is proportional to the value of K_i. Table 2 presents the values of K_I for the textured GMB at various temperatures and incubation times. In estimating K_I, the following assumptions were adopted:
The applied tensile stress in NCTL test (σ) = 30%×σ_y = 9.6 kN/m;
W= a + variable ligament thickness (l). The crack depth (notching depth) was assumed approximately constant and equals 20% of the nominal thickness of the GMB, thus the only variable is assumed to be the ligament thickness.

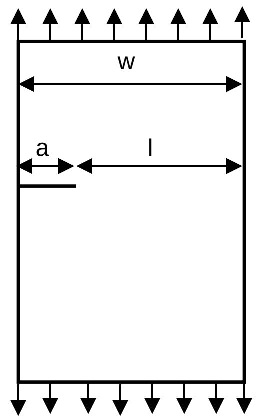

Figure 1. Finite plate with edge crack loaded with uniaxial tensile stress.

The results (Table 2) showed that K_I had a limited effect on the SCR results compared to the surface defects. This can be explained by comparing *Ki* and the SCR values obtained from experiments. For instance, the SCR of the 8-month aged GMB at 85°C (Table 2) was 1704 hours (ligament thickness= 1.1875 mm; K_I=0.4058 kPa.m$^{0.5}$) and 125 hours (ligament thickness= 1.2125 mm; K_I=0.4034 kN/m$^{0.5}$). These results mean that the specimen that had less ligament thickness and a subsequently higher K_I and *da/dt*, had a greater SCR. This implies that variability in the material and surface defects had the dominant effect on the variability of SCR.

Table 2. Stress intensity factor and SCR for 8-month aged textured GMB at 85°C.

a (mm)	*l* (mm)	*w* (mm)	σ (kN/m)	K_I (kPa.m$^{0.5}$)	SCR (hours)
0.3	1.1875	1.4875	9.6	0.4058	1704
0.3	1.2	1.500	9.6	0.4046	2226
0.3	1.2125	1.5125	9.6	0.4034	125

3.2. Investigation of the Fracture Plan of NCTL Broken Specimens

The environmental scanning electron microscope (ESEM) photos of the cross section of broken specimens in the NCTL test suggest a difference in the failure mechanism for the textured GMB specimens as inferred from the shape of the fracture surface; this may explain the great variation in the SCR results. Figure 2 shows the fracture surface of one of the unaged specimens tested for the smooth edge of the textured GMB examined (same resin). The SCR of this specimen was 4900 hours and the failure was brittle. On the other hand, the fracture mechanism for the textured GMB was not brittle in all cases because the surface defects and discontinuities in the textured GMB's surface affected the failure mode and resulted in the high variability in the SCR results. For instance, Figure 3 shows the failure surface of unaged textured SCR specimen that failed in the NCTL test after 2700 hrs. The failure surface was smooth with a pattern of torn fibrils similar to the failure plane of the smooth edge specimen (Figure 2). Figure 4 shows the failure surface of unaged textured specimen with SCR of 150 hours. The fracture plane does not show any torn fibrils but just shows an excessive plastic deformation suggesting a ductile failure.

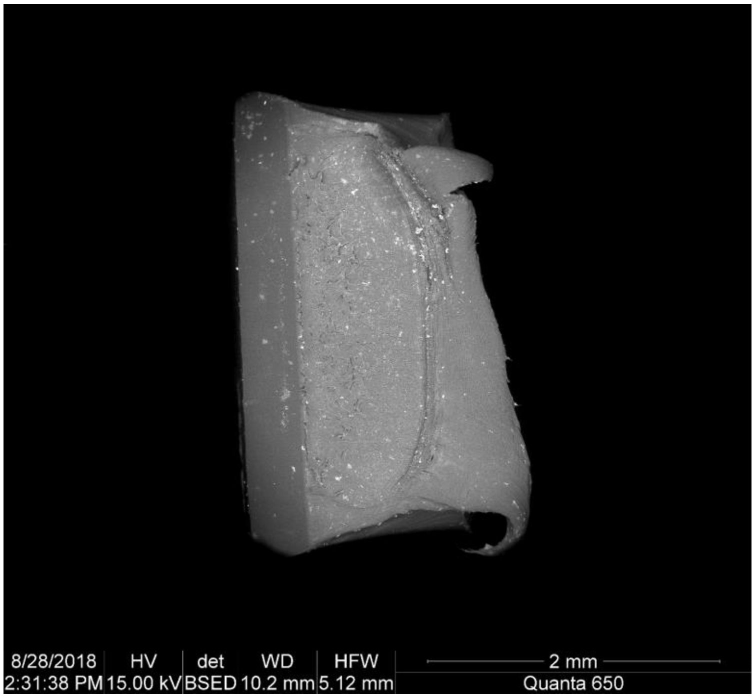

Figure 2. Fracture surface of a NCTL specimen of unaged smooth edge; SCR = 4900 hours.

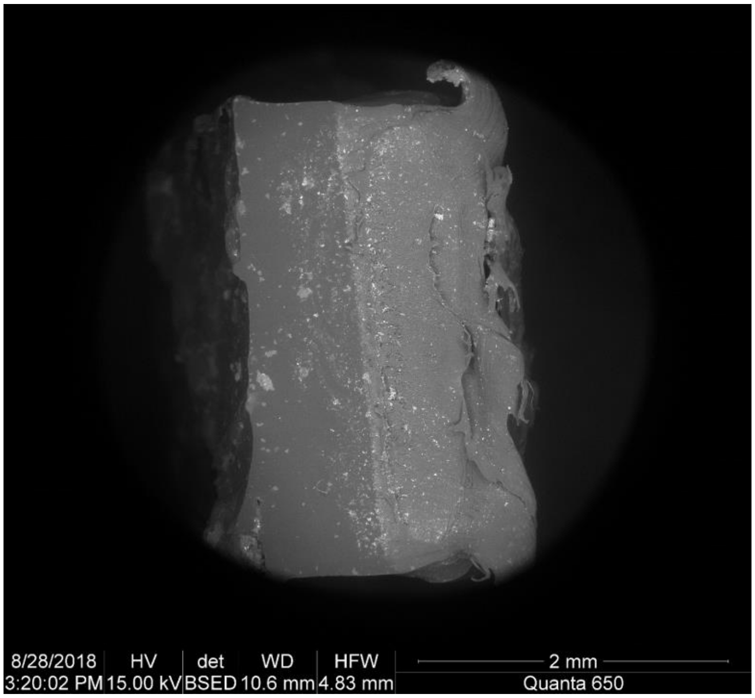

Figure 3. Fracture surface of a NCTL specimen of unaged textured specimen; SCR = 2700 hours.

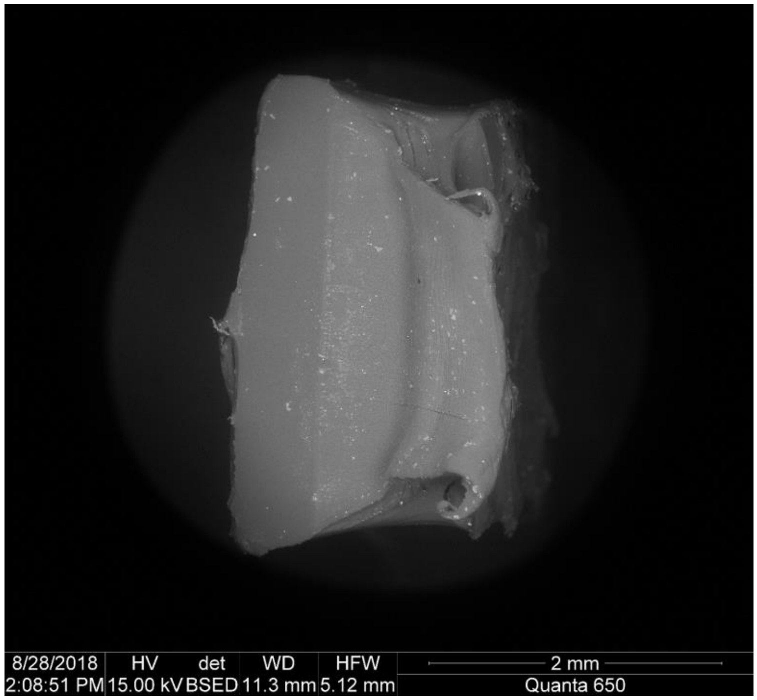

Figure 4. Fracture surface of a NCTL specimen of unaged textured specimen; SCR = 150 hours.

4. CONCLUSIONS

The sources of variability of SCR for a double-sided 1.5 mm-core thick textured GMB estimated using the NCTL test was investigated by comparing the stress intensity factor and the laboratory results of the NCTL test. This comparison and the ESEM pictures for the fracture surface of the SCR specimens tested suggest that the textured blown-film GMB is likely to be somewhat more susceptible to stress cracking due to low local SCR values and variability in thickness (stress concentrations) as well as potential defects and/or discontinuities on the textured GMB surface. In absence of more evidence, this suggests that engineers should be more conservative in selecting the maximum allowable strains for textured GMBs compared to smooth counterparts. This study did not examine texturing by lamination, impingement, structuring, however it is suggested that each of these texturing methods has its own potential challenges and also need investigations before any conclusion is reached as to which method is preferable. Due to the paucity of research dealing with performance of all forms of textured GMBs, it is recommended that textured GMBs only be used where essential to ensure slope stability and not simply for construction convenience on relatively flat landfill base where stability issues can be avoided by other means.

5. ACKNOWLEDGEMENTS

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