Physical Performance of a Bituminous Geomembrane for use as a Basal Liner in Heap Leach Pads

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ABSTRACT
Bituminous geomembranes (BGMs) have been used in barrier applications such as canal linings, tailings facility liners, and as waste covers however there is a paucity of data on their use as basal liners under high overburden stress, such as the case of heap leach pads. Heap leach pads present a challenging environment for any geomembrane; in many cases a coarse drainage layer is in direct contact with the geomembrane. This paper examines the performance of a 4.0 mm BGM with respect to gravel puncture, strains, and leakage in a unique testing apparatus. It was found that this particular BGM showed a good resistance to leakage, at heads less than 10 m, even with a significant number of gravel punctures suggesting a "sealing" interaction between the gravel and bitumen.

RÉSUMÉ
Les géomembranes bitumineuses (BGMs) sont utilisées dans des applications de barrières étanches comme des canaux, des stockages de résidus miniers, et des couvertures de centre d'enfouissements techniques. Cependant, il existe très peu de données sur l'utilisation de ces géomembranes comme barrière d'étanchéité sous des contraintes élevées, comme celles existantes dans les installations de lixiviation en tas. Ces installations représentent un contexte très contraignant pour toutes les géomembranes. Dans de nombreux cas, une couche de drainage grossier est en contact direct avec la géomembrane. Cet article étudie la performance d'une Géomembrane Bitumineuse de 4 mm d'épaisseur, prenant en considération, des perforations engendrées par des graviers, la pression, et les débits de fuite avec un appareillage d'essai unique. Il a été constaté que cette BGM spécifique présentait une bonne résistance aux fuites, avec une hauteur d'eau de moins de 10 m, malgré un nombre significatif de perforation dues aux graviers. Cela suggère qu'il y a une interaction « étanche » entre le gravier et le bitume.

1 INTRODUCTION

Heap leaching is a common mining process to recover metals such as gold, copper, and uranium from mined ore (Lupo 2010). The process works by crushing and stacking the ore in 5 – 10 m thick lifts up to a certain height over a geomembrane lined pad (Breitenbach 2005). A high or low pH chemical solution (depending on the target metal) is dripped from an irrigation system and becomes what is known as the 'pregnant leach solution' (PLS) after it percolates through the ore and extracts the metal of interest (Fourie et al. 2010).

The main function of the geomembrane is to minimize the loss of PLS (and hence valuable metals) but also to protect the environment (Rowe et al. 2013). Geomembranes are an excellent barrier for containing fluids except where there are holes (Rowe 2012). Holes in the geomembrane can arise from a number of sources such as installation activities, gravel puncture, and much later on, for polyethylene, from environmental stress cracking. The focus of this paper however is only on those holes caused by static gravel puncture under high overburden stresses.

Heap leach pads are one of the most challenging geomembrane applications. In most cases, the geomembrane is in direct contact with a coarse drainage layer comprised of either crushed rock or run-of-mine ore (Lupo 2010). Geomembrane protective cushions (e.g., geotextiles) are seldom used because of stability concerns but also because it is not economically feasible given the massive size of most heap leach projects (Thiel and Smith 2004). In the 1990s, ore heights were pushing 50 m however today it is not uncommon for them to exceed 100 m, which is greater than 2 MPa of overburden stress on the liner (Thiel and Smith 2004). Additionally, hydraulic heads can reach up to 30 m for "valley fill" type pads which have internal PLS storage however for conventional pads the heads are typically less than 1 m.

In order to assess whether a certain geomembrane is compatible with the site-specific materials (gravel drainage layer, subgrade etc.), the cylinder test method (aka., liner load test) should be performed (as described in ASTM D5514; Shercliff, 1998; Brachman et al. 2000; Thiel and Smith, 2004; Lupo and Morrison 2007). This performance test can provide evidence of short-term damage to a GMB in the form of (1) punctures and (2) excessive strains. Such testing has been reported in the literature for HDPE, LLDPE, and PVC; however, there is a paucity of data on bituminous geomembranes (BGM). This paper presents the preliminary results of cylinder performance testing of a 4 mm-thick elastomeric BGM under simulated heap leach pad loads and hydraulic heads.

2 MATERIALS & METHODS

2.1 Bituminous geomembranes (BGMs)

A bituminous geomembrane (BGM) is a multicomponent geomembrane made by impregnating and coating a nonwoven geotextile with a special blend of bitumen. The most common type of BGM (and the one examined in this paper) is the “elastomeric BGM” which uses a blend of bitumen that has been modified with the elastomer styrene-butadiene-styrene or “SBS”, (Touze-Foltz and Farcas 2017). Elastomeric BGMs have gradually replaced their predecessor, the Oxidized BGM, because of their superior resistance to UV (Touze-Foltz et al. 2015). The elastomeric bitumen gives the BGM its waterproofing properties while the geotextile gives the BGM its strength and mechanical properties such as tensile strength and puncture resistance. A cross-section of the BGM tested with its various components is shown in Figure 1 and some of its properties are listed in Table 1.

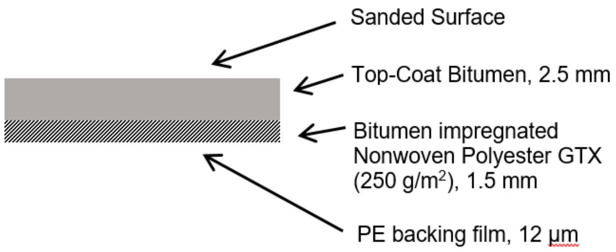


Figure 1. Cross-section of the BGM used in this study

Table 1. Some Properties of this BGM[1]

Property[2]	Value	Units
Avg. Thickness	4.0	mm
Tensile Strength MD (XD)	23 (20)	kN/m
Break Elongation MD (XD)	45 (48)	%
Static Puncture Resistance	460	N
Cold Bend Test	-25	°C

[1] Siplast® Teranap 431-2M (http://www.siplast-international.com). Values from manufacturer data sheet

[2] From applicable ASTM standards

2.2 Load Test Method

Testing was based on Rowe et al. (2013) who studied puncture and strains for a 1.5 mm HDPE geomembrane under simulated heap leach pad loading conditions using a unique cylindrical apparatus with an inside diameter of 590 mm and height of 500 mm (Figure 2). This cell can apply vertical pressures up to 3000 kPa with essentially zero horizontal strains due to the thickness of the steel cell walls. Friction along the cell walls was minimized by using two layers of 0.1-mm-thick polyethylene (PE) sheets with a high-temperature bearing grease between the sheets. The friction treatment was protected by a geotextile layer with a series of plastic strips arranged in rings. This combination of friction treatment and protection rings has been shown to reduce the boundary friction to less than 5° (Tognon et al. 1999) allowing for 95% of the applied vertical stress to transfer to the geomembrane (Brachman and Gudina 2002).

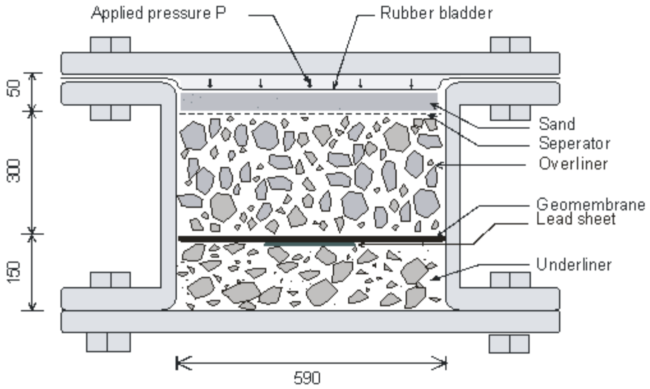


Figure 2. Geosynthetic Liner Longevity Simulator (dimensions in mm)

Testing the BGM under the same conditions used by Rowe et al. (2013) provided a means of comparison between BGM and HDPE. Rowe et al. (2013) tested six different underliners. Except for UL-1, which fell outside the envelope, the grading curves for each were selected based on the grain size envelope complied by Lupo and Morrison (2007) who surveyed of a number of heap leach pad underliners (Figures 3 and 4). The overliner (OL) was constant across the series to isolate the effect of the underliner.

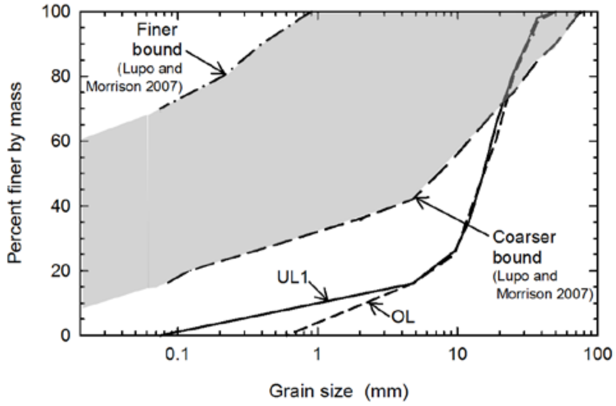


Figure 3. Grain size distribution of underliner (UL-1) and overliner (OL) used in this study and bounds of heap leach pad underliners (shaded area) reported by Lupo and Morrison (2007).

Underliner UL-1 was selected to be coarser than the envelope defined by Lupo and Morrison (2007) to represent a more aggressive case sometimes encountered in practice. These were the same grading curves for the underliner and overliner used to examine puncturing and strains in 1.5 mm HDPE (studied in Rowe et al 2013) which resulted in a significant number of holes (nine pin-holes or about 320,000 hole/ha). Thus, this case was selected for the first BGM performance test to compare gravel puncture.

Figure 4. Underliner gravel used (overliner was essentially the same).

The underliner was compacted to modified proctor in three (3) equal lifts in the cell. Next, a 270 mm square 0.4 mm thick, soft lead sheet was centered on the top surface of the underliner to permanently preserve the deformations at the applied overburden stress. A 590 mm diameter sample was cut from the BGM roll and placed, sanded side up, followed lastly by the overliner gravel. After closing the cell, the load was applied in increments of 200 kPa every 10 min up to the test pressure of 2000 kPa which was maintained for a duration of 100 hours, in accordance with Rowe et al. (2013).

2.3 BGM Strain Calculation Method

The most significant indentations on the BGM underside were scanned using a laser profiler (Figure 5) and strains were computed by the method of Tognon et al. (2000) which utilizes a coupled membrane-bending theory to calculate the strain distribution along an indentation profile.

The distribution of strain is non-linear and varies significantly across the width of an indentation profile. Thus, the Tognon method allows the engineer to estimate the “peak local strain” as opposed to computing the average strain across the indentation. Taking the average strain (i.e., the arch-elongation method) has been shown to significantly underestimate the peak local strain (Tognon et al. 2000).

For most conventional geomembranes (e.g., HDPE), gravel indentations are considered to be “plane-strain” deform-ations such that the neutral axis of bending is in the center of the geomembrane thickness (similar to a structural beam). However, for composite materials like BGMs, this assumption does not hold true since their total thickness is composed of two completely different materials; soft elastomeric bitumen over an axially stiffer nonwoven geotextile core (see Figure 1). Since the mechanical stiffness of the soft bitumen top coat is essentially zero compared to the stiffness of the underlying geotextile, it is the geotextile that takes the bending and membrane stresses induced by a gravel indentation. Since the thin lead sheet was placed beneath the BGM (touching the geotextile) the indentations can be used to calculate strain in the geotextile.

Therefore, the thickness term in the Tognon et al. (2000) equation should not use the gross BGM thickness *but rather* the thickness of just the geotextile component (1.5 mm in this case). Using the gross BGM thickness in such strain calculations will severely over-estimate strains.

Figure 5. Laser profiler

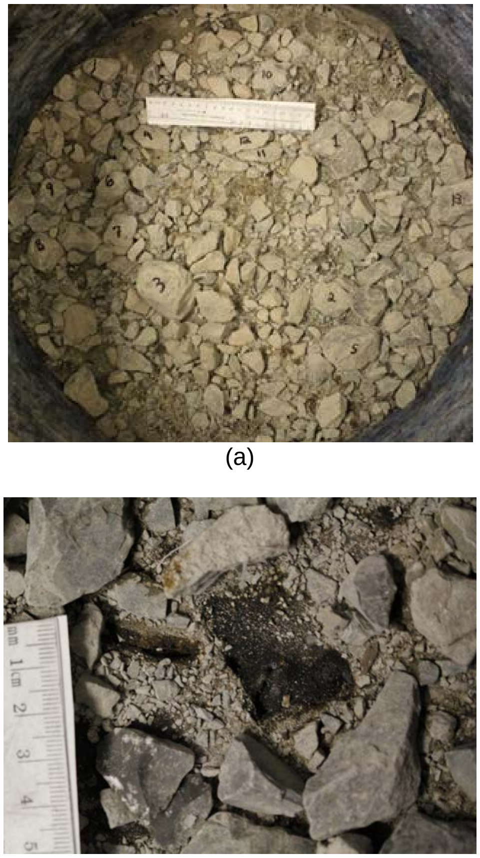
3 RESULTS & DISCUSSION

3.1 Puncture

After 100 hours under 2 MPa stress, the test was ended and the lid was opened. The overliner gravel was removed and it was observed that gravel in contact with the BGM appeared to be embedded into the bitumen. A vacuum was used to gently remove the loose material, sand, and rock dust from around these embedded particles which revealed that almost all the gravel particles were firmly stuck into the bitumen topcoat (Figure 6). There appeared to be a “sealing effect”- at least visually- between bitumen and gravel (discussed more in Section 3.3).

The same type of gravel embedment was seen on the BGM underside (from the underliner); however only half of these particles, or so, were attached. This was likely a result of the plastic film “backing” on the BGM underside which didn’t offer as good a bond as the sticky bitumen top coat.

To detect punctures, all the embedded particles were removed by hand and back-lit photographs were taken. There is some debate as to whether the particles had become part of the BGM system (see Section 3.3) since they were so well adhered to the bitumen. In many cases, the particles were firmly lodged and difficult to remove- However, pulling them out was the only way to detect the presence of holes. The back-lit photographs were taken in a special dark box that sealed the BGM sample so that a bright florescent light could only pass through the BGM holes (Figure 7).



(a)

(b)

Figure 6. (a) Embedded particles after vacuuming loose debris away (b) Close up of the top surface also showing area where gravel was removed forcefully by hand.

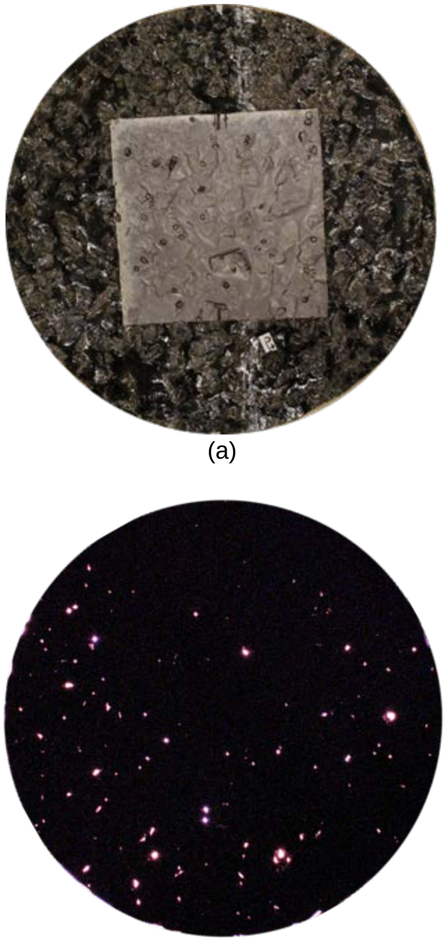
The HDPE equivalent of this test performed by Rowe et al. (2013) resulted in nine (9) pin-holes. At first glance, this may appear bad for the BGM (which had 115 holes) but as will be shown later, the vast majority of these holes appear to be well-sealed and hydraulically insignificant.

3.2 Strains

Seven of the most significant looking indentations on the lead sheet were scanned with a laser profiler and the strains were computed using the method of Tognon et al. (2000). The largest strain was found to be 150% which is much larger than that of HDPE from previous work under the exact same test conditions (40%). A comparison of the 7 largest strains in BGM and HDPE is shown in Figure 8.

The fact that the BGM strains were significantly higher than those for the HDPE and the fact that this BGM's tensile break elongation is much less than HDPE (due to the nonwoven geotextile) helps to explain the number of BGM punctures in this test.

The strains in this particular BGM are higher than HDPE because of the nonwoven geotextile carrier's flexibility and compressibility which permit extremely sharp indentation profiles.



(a)

(b)

Figure 7. (a) BGM underside with lead sheet (b) Same view but with back-lit photograph exposing 115 holes.

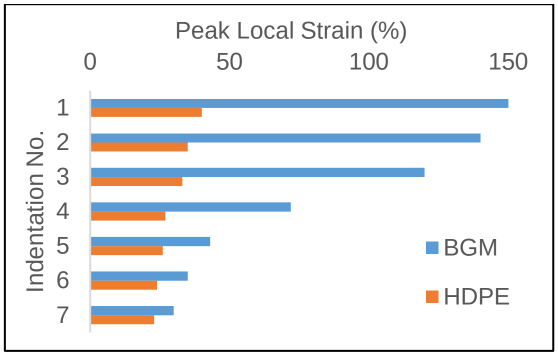
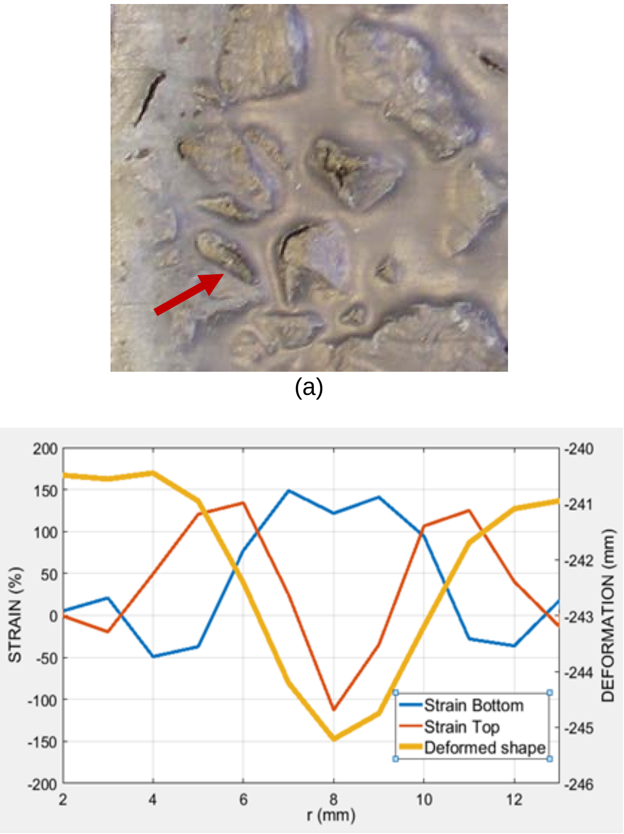


Figure 8. Comparison of seven largest strains in BGM from this test and HDPE from previous work by Rowe et al. (2013).

The indentation which produced the peak local strain of 150% is shown in Figure 9 along with its strain distribution.



(a)

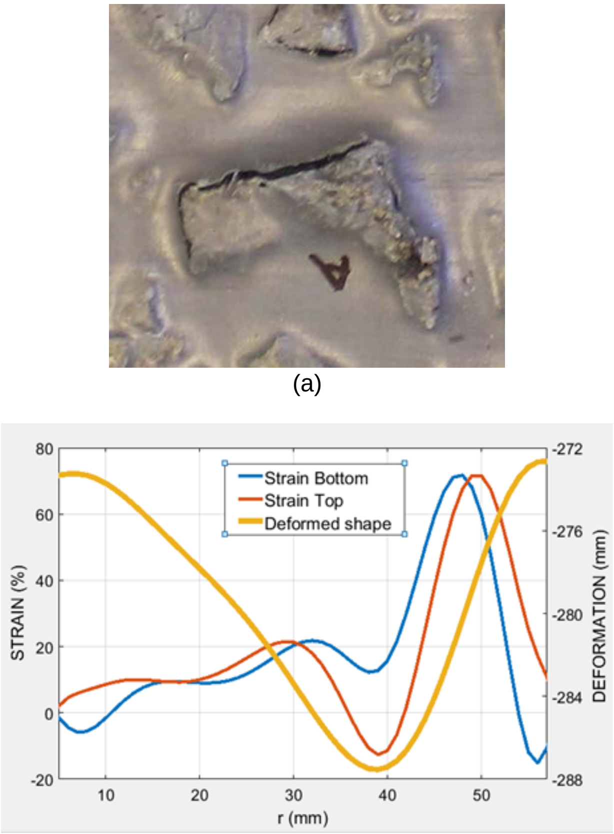
(b)

Figure 9. (a) Location of peak strain indentation (b) strain distribution with peak local strain of 150% (note how strains vary across the indentation)

This indentation, measuring 6 mm wide by 5 mm deep, was much smaller than most of the other indentations (as shown in Figure 9a) however because of its sharpness, it produced the largest peak local strain. The largest indentation by comparison measured 45 mm wide and 16 mm deep but only resulted in a peak local strain of 72% (Figure 10). Sharpness of the indentation (i.e., rate of change in slope), at least for this particular BGM, appears to be more significant for strains than the overall size of the indentation.

3.3 Preliminary Leakage Test

The numerous holes, combined with the observed gravel embedment in the bitumen, prompted a leakage test as a preliminary assessment of the efficacy of the gravel-bitumen seal. This test was essentially a repeat of the first test (using the same cell, materials, overburden etc.) except that no lead sheet was used and a head of water, which ranged from 0.3 to 30.0 m, was maintained in the overliner. A sealing technique developed by Joshi (2016) was used to hydraulically isolate the cell area above the BGM from the area below it. Leakage was monitored for a period of 165 hours at an initial overburden stress of 2,000 kPa (see Table 2).



(a)

(b)

Figure 10. (a) Location of largest indentation measuring 45 mm wide and 16 mm deep (b) strain distribution with peak local strain of 72%.

Table 2. Leakage Results

Head (m)	Leakage (L/hr)	(L/ha/d)
0.3	0	0
1	0	0
10	0.0012	1136
30	0.004 -> 0.010	3545 -> 8900

The leakage at a head of 0.3 and then 1 m were monitored for 10 hours; however, no leakage was detected so the head was increased to 10 m. At 10 m head, some leakage was detected so the head was held constant for 40 hours giving a steady-state leakage of 0.0012 L/hr. The head was then increased to 30 m with a corresponding initial steady-state leakage rate of 0.004 L/hr. However, after 80 hours of testing, the flow rate suddenly increased to 0.01 L/hr. It is hypothesized that this sudden increase was due to time dependent gravel crushing and fracture.

Although Rowe et al. (2013) did not measure leakage experimentally as was done in this study, a theoretical estimate of leakage can be made using geomembrane hole equations (eg. Rowe 2004). Since both the overliner and underliner were coarse gravel, the hydraulic resistance of both materials was negligible and Bernoulli's equation was used (Eq. 1).

$$Q = \pi C_B r_o{}^2 \sqrt{2gh_w} \qquad [1]$$

where r_o is the radius of geomembrane hole (m), C_B is dimensionless coefficient related to the sharpness of the hole edges, g is acceleration due to gravity (m/s^2), and h_w is the hydraulic head acting over the hole (m). Using a reasonable assumption of r_o = 0.1 mm for each of the nine (9) HDPE pin-holes the calculated leakage was about 1,250,000 L/ha/d at a head of 10 m (the first head where BGM leakage was detected). This leakage rate assumes no obstruction to flow by the gravel particles above and below the HDPE hole, which is conservative. If we were to assume that 8 of the 9 holes were well-plugged such that only one single hole (with r_o = 0.1 mm) permitted leakage, the calculated HDPE leakage reduced to 140,000 L/ha/da at 10 m head which is still almost 140 times greater than the BGM leakage at that head. In this context, this particular BGM may be considered to have performed better than the 1.5 mm HDPE geomembrane. Based on this preliminary work, it appears that the BGM sealing effect worked reasonably well. However, there are limitations. One limitation is the durability of the gravel plugging the hole, specifically regarding its susceptibility to fracture (Figure 11).

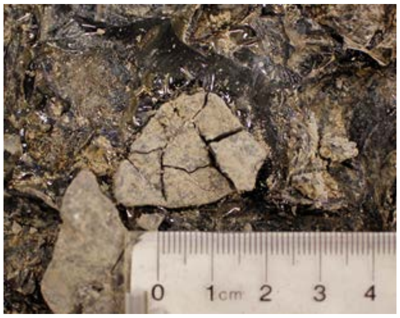


Figure 11. Example of gravel crushing from high overburden stresses in the leakage test

Fracturing or degradation of the gravel plugging a hole may significantly compromise its ability to seal the hole therefore gravel properties such as compressive strength may be an important consideration for BGMs. Since the gravel we used in this short-term test was limestone (a relatively weak rock), almost half of the gravel fractured to some degree (minor corner chips or full particle crushing) so the BGM leakage response reported here could possibly improve with increasing gravel compressive strength.

4 CONCLUSION

This paper examined punctures and strains for a certain 4 mm BGM in a highly aggressive environment involving a coarse gravel underliner, 2000 kPa overpurden pressure, and a coarse overliner in direct contact with the BGM. The test procedure was based on a heap leach pad study by Rowe et al. (2013) of puncture and strains in a 1.5 mm HDPE geomembrane and as such, a direct comparison was made between the two different liners. The results indicated that there was more physical damage to this BGM than the HDPE (in the form of holes) however a subsequent leakage test suggests that the gravel appears to have sealed the holes in place. Even though this BGM had more holes than the HDPE, its leakage was much less. Lastly, there are some limitations which may compromise a good sealing effect between gravel and bitumen, such as gravel crushing and fracture (and possibly gravel dissolution in high or low pH mining solutions). It is cautioned that this research is still in the initial stages and more investigation is required; however, the results are promising.

5 ACKNOWLEDGEMENTS

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