A new way to interpret the geomembrane index puncture resistance test

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ABSTRACT
In North America, the geomembrane puncture resistance index test (ASTM D4833) is primarily used as a means of manufacturing quality control, however—because of the name—it is sometimes assumed to have a relationship to puncture resistance in the field. To explore the implications of this assumption, seven different geomembranes are examined using the index puncture test and a performance test which simulated an aggressive heap leach pad loading condition with a coarse drainage layer in direct contact with the geomembrane. It is found that the approach adopted in ASTM D4833 of reporting the peak force as the "puncture resistance" can sometimes be a misleading indictor of real puncture resistance when certain geomembranes are compared but it is a good indictor when different thicknesses of the same geomembrane are tested. There are, however, ways of interpreting the index test other than taking the peak force such as measuring the offset-tangent modulus, break properties, and puncture toughness. It is found that the puncture break elongation can sometimes have a better correlation to field puncture resistance in some situations (such as deep burial) suggesting that both geomembrane strength and extensibility are important properties despite the fact that ASTM D4833 only says to report the peak force.

Keywords: Geomembrane puncture, Index test, Performance test, deep burial, Bituminous geomembranes

1. INTRODUCTION

Geomembranes (GMBs) are excellent barriers to advective flow except where there are punctures, tears, or faulty seams (Rowe 2012). In the short-term, punctures are ductile and occur during placement of the GMB, placement of the overliner (typically a coarse drainage layer), and—after the facility is filled—from excessive hydrostatic pressures (e.g., dam) or geostatic overburden pressures (e.g., heap leach pad). Brachman et al. (2011) referred to these as ductile tears. In the long-term, polymeric GMBs such as high-density polyethylene (HDPE) are susceptible to environmental stress cracking and can fail in a brittle manner if the exposure conditions are not appropriately accounted for (e.g., liner temperature, leachate composition, and gravel induced tensile strains). Although it is sometimes not possible to control liner temperature or leachate strength, it is possible to limit the induced tensile strains with good design and construction and there has been significant developments in recent years on how to measure and reduce these strains (e.g., Abdelaal et al. 2014; Eldesouky and Brachman, 2020). While limiting tensile strains in the GMB is necessary for good long-term performance, the focus of this paper is on short-term "ductile" punctures.

Punctures that arise during GMB installation and placement of the overliner can be located with a leak detection survey and patched, however, those arising from excessive vertical pressures after the facility is filled cannot be repaired. This category of puncture can only be avoided through good design and this requires some form of geomembrane puncture testing. Narejo et al. (1996) proposed three categories of puncturing testing: (1) performance tests (2) quasi-performance tests and (3) index tests. Performance tests simulate the field condition as closely as possible by using a site-specific subgrade, overliner, and anticipated stress if the application is geostatic puncture (e.g., a landfill) or by using water pressure directly above the GMB and gravel below if the application is hydrostatic (e.g., rockfill hydro-dam). The former are called liner load tests and the GMB is exhumed afterwards to inspect for damage (as described in ASTM D5514-Procedure C; Lupo and Morrison 2007; Rowe et al. 2013). The latter are called hydrostatic puncture tests and assess damage during the test by monitoring for leaks (as described in ASTM D5514-Procedure B; Lambert 2002; Marcotte et al. 2009). Index puncture tests—most notably ASTM D4833—are much easier to perform however they do not simulate the field. Lastly, quasi-performance puncture tests are somewhere between the two extremes (e.g., truncated cone hydrostatic puncture test).

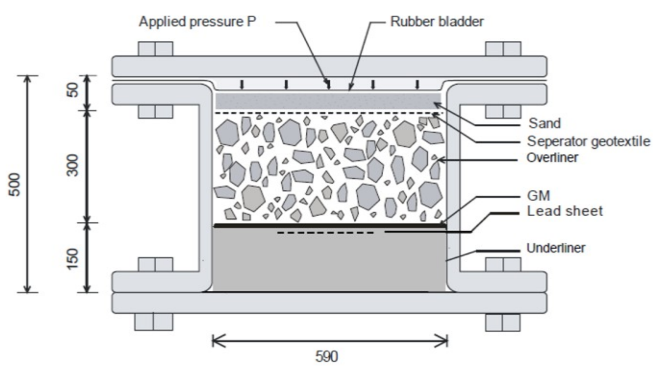
Being an index test, ASTM D4833 should not be used to assess GMBs for their real puncture resistance in the field. That said, one with the fact cannot ignore that this index property, called the "GMB puncture resistance" (expressed in Newtons), is listed on virtually every GMB data sheet. Therefore, it is not unreasonable to imagine that some will think this value has a relationship to the field. Thus, the question remains: What correlation—if any—does this index test have to the real puncture resistance of a GMB? Most LLDPE GMBs have a lower ASTM D4833 "puncture resistance" than most HDPE GMBs but the perception of many designers is that LLDPE is more puncture resistant than HDPE since they have lower crystallinity and higher extensibility than HDPE. The perception may also be related to the fact that thinner LLDPE is often used, without appropriate justification, in the field as an alternative to a thicker HDPE for the same application and due to a difference in thickness it looks and feels more flexible.

When the thickness is the same, however there is evidence to suggest LLDPE is more puncture resistant than HDPE. For example, Rowe et al. (2013) examined a 1.5-mm HDPE GMB and a 1.5-mm LLDPE GMB in the same aggressive heap leach pad loading condition and found more holes in the HDPE (5 holes) than in the equivalent LLDPE test (3 holes) despite the fact that the average index puncture resistance of the 1.5-mm HDPE was 16% higher than the 1.5-mm LLDPE. Moreover, recent (unpublished) testing on bituminous geomembranes (BGM) at Queen's geo-lab has further revealed a disconnection between the index and performance test. On the other hand, Lambert (2002) reported a correlation between the index test and the hydrostatic puncture test, however, the geostatic loading was not considered. Therefore, the objective of this study is two-fold; (1) to explore if a correlation exists between the index puncture test and geostatic performance test (e.g., heap leach pad), and (2) to explore other ways of interpreting the ASTM index test load-elongation curve (e.g., yield, break properties, toughness) and their usefulness.

2. METHODS & MATERIALS

2.1 *Performance test method - Deep burial Simulation*

The performance test method was the same as Rowe et al. (2013) who studied the strains and puncture behavior of 1.5-mm HDPE and LLDPE GMBs under simulated heap leach loading conditions using a unique cylindrical apparatus with an inside diameter of 590-mm and height of 500-mm (Figure 1a). Unlike quasi-performance tests which use a rubber underliner mat or truncated cones, this apparatus can be considered a *true performance test* simulating geo-static loading with site-specific materials above and below the GMB (i.e., a real element at the bottom of a lined facility). Vertical pressure was applied by fluid acting on a rubber bladder in increments of 20 kPa / min to the target pressure which was then held constant for 100 hours. Stark et al (2008) found no difference in puncture outcome between this rate and the slower rate of 7 kPa/30 min specified by ASTM D5144. Boundary friction on the side wall was mitigated by using grease sandwiched between two 0.1-mm thick plastic sheets which Brachman and Gudina (2002) showed allows for over 95% of the applied vertical stress to reach the GMB and underliner soil. A geocomposite drain placed at the bottom of the cell enabled consolidation of underliner G2 which contained 15% fines.



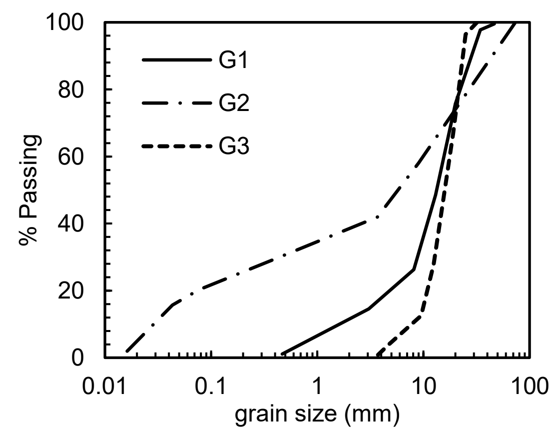


Figure 1: (a) the 590 mm diameter test cell used for the performance tests and (b) grain size distributions for the gravelly underliners and overliners examined in this study.

The grain size distributions of the underliners and overliners examined are shown in Figure 1b. Soils G1 and G2 were identical to overliner OL-1 and underliner UL-2 from Rowe et al. (2013), respectively. G1 was a crushed limestone gravel at the transition between GW and GP and matched the coarser bound of heap leach pad overliners (typ. drainage layer) surveyed by Lupo and Morrison (2007). G2 was a sandy gravel re-compacted till containing 15% fines and matched the coarser bound of heap leach pad underliners surveyed by Lupo and Morrison (2007). G3 was a poorly graded crushed gravel (GP) sourced from a local granite quarry was slightly more aggressive than G1.

Two performance test cases were examined in this study (Figure 2). Case 1, the replica of Rowe et al. (2013) (G1 above, G2 below, 2 MPa), was used to explore the relative puncture behavior of different types of GMB of mostly similar thickness while Case 2 (G3 above and below, 1.5 MPa) was used to explore the effect of GMB thickness on puncture behavior. Since G1 and G2 both matched the coarser bounds of overliners and underliners examined by Lupo and Morrison (2007), respectively, and G3 was poorly graded gravel, Cases 1 and 2 can both be considered extremely aggressive however, being a study of puncture, these severe conditions were warranted.

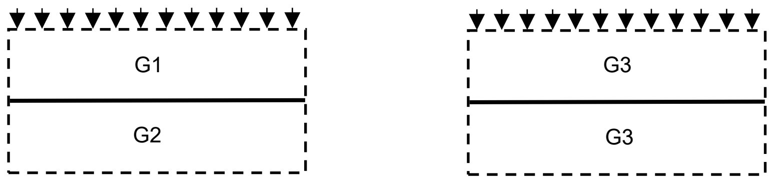


Figure 2: The two performance test cases examined

The 150-mm thick underliner soil was compacted in three (3) equal 50-mm thick lifts using a modified compaction procedure that achieves the same energy as standard proctor but allows for the larger size of the cell. G2 (sandy gravel with 15% fines) was the only soil that required moisture conditioning and it was compacted in the cell at a gravimetric water content of 3.2%. G3 underliner was compacted air dry (~ w=0.4%). Next, the 0.59-mm GMB sample was placed followed by the 300 mm-thick coarse overliner layer which was not compacted (to simulate a gravel drainage layer).

Following the test, the GMB was exhumed and the damage assessed using a special dark box where only a bright florescent light can only pass through the punctures. For BGM, the gravel particles became firmly embedded into bitumen and had to be carefully removed by hand in order to reveal the punctures. This gravel embedment is unique to BGMs and can render many of the holes hydraulically insignificant in the short-term however, removing the gravel was the only way to see the damage (e.g., Clinton and Rowe, 2017).

2.2 *Index puncture testing & interpretation*

Index puncture tests were performed following ASTM D4833. A universal testing machine with 20 kN load cell (accuracy +/- 0.5 N) advanced the probe at 300 mm/min until perforation. Force (N) and displacement (mm) data was acquired at 50 Hz (50 data points per second) providing high resolution force-elongation curves for subsequent interpretation. Five specimens from each GMB were tested (n=5) and the mean and standard deviation of properties was reported.

Although ASTM D4833 only says to report the peak force as the “puncture resistance” (Point II, Figure 3), other properties exist on the force-elongation curve. For polyethylene GMBs, there are three (3) distinct points: (I) yield (II) peak (III) puncture and since there are two (2) properties at each point—force (N) and elongation (mm)—and that puncture toughness (N-m) and initial elastic modulus (N/mm) can be measured, there are eight (8) different properties one can obtain from a single ASTM D4833 puncture test. For BGMs, however, there is only one point of interest since rupture occurs at the peak and there is no distinct yielding beforehand; This is characteristic of NW-GTXs (of which BGMs are made from). The residual force after BGM puncture is due to friction between the bitumen and steel probe; It was ignored in the toughness calculation.

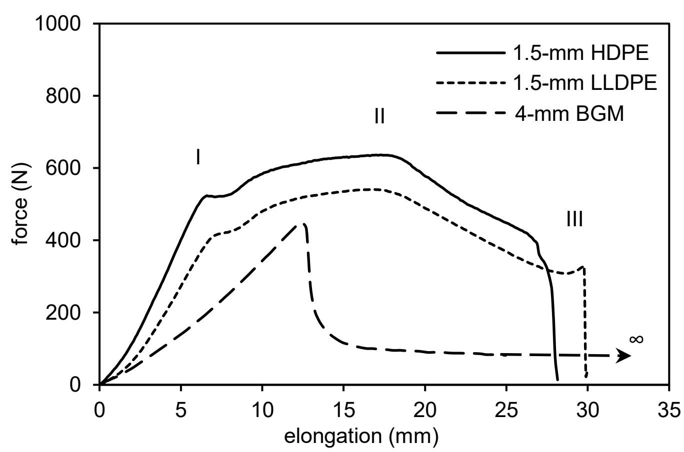


Figure 3: Typical index puncture load-elongation behavior for polyethylene (PE) GMB and BGM.

The yield point was selected to be the data point directly below the intersection of two tangents approaching yield. The off-set tangent modulus was selected as the slope of the linear portion elastic region which also crosses the yield point. Puncture toughness was calculated by using Riemann sum approximations (mid-point method) with delta x = 0.1-mm spacing that approaches the definite integral (i.e., area under the curve).

2.3 *Geomembranes examined*

The key properties of the GMBs examined are shown in Table 1. The GMBs covered a wide range of materials (HDPE, LLDPE, BGM), types (smooth, textured), and thicknesses. It should be noted that that the LLDPE GMB was towards the higher end of typical LLDPE density for improved chemical resistance. Also, it is worth noting that HDPE is really medium density polyethylene (MDPE) that falls into the high-density category after the addition of carbon black (Islam et al. 2011).

The smooth HDPE GMBs used to isolate the effect of thickness (GMB5, GMB6, GMB7) were from the same formulation and manufacturer only they were produced at different thicknesses. It should be noted that using PE GMB less than 2-mm under such aggressive gravel loading is uncommon however it was done deliberately here to create punctures (and hence facilitate a comparison). The 0.5-mm thick GMB was used for research purposes.

Table 1. Key properties of the geomembranes examined (mean ± standard deviation)

		Case 1: Effect of GMB type				Case 2: Effect of GMB thickness		
		GMB1	GMB2	GMB3	GMB4	GMB5	GMB6	GMB7
Nominal thickness (mm)		1.5	1.5	4.1	2.0	0.5	1.0	2.0
Type	ASTM	HDPE	LLDPE	BGM	text. HDPE	HDPE	HDPE	HDPE
Puncture resistance (N)	D4833	638 ± 7	551 ± 15	445 ± 24	788 ± 25	297 ± 6	493 ± 6	774 ± 10
Crystallinity (%)	E794	48	38	n/a	unknown	53	53	46
Resin Density (g/cc)	D1505	0.937	0.924	n/a	unknown	0.937	0.936	0.936
GMB Density (g/cc)	D1505	0.947	0.936	n/a	> 0.940	0.947	0.946	0.947
Tensile break strength (kN/m)[1]	D6693	46 ± 5	52 ± 7	22±2[3]	38 ± 15	19 ± 1	34 ± 1	66 ± 4
Tensile break strain (%)[1]	" "	825 ± 81	880 ± 104	44±3[3]	474 ± 183	768 ± 45	784 ± 14	830 ± 38
Tensile break strength (kN/m)[2]	" "	44 ± 6	54 ± 2	19±1[3]	18 ± 15	20 ± 1	35 ± 1	66 ± 3
Tensile break strain (%)[2]	" "	830 ± 95	980 ± 34	52±4[3]	295 ± 164	909 ± 44	852 ± 37	854 ± 33

[1]Tested in the machine direction
[2]Tested in the cross-machine direction
[3]Tested according to ASTM D7275 (the BGM tensile standard)

3. RESULTS

3.1 *Index puncture test results*

The eight properties obtained from the index puncture test for the GMBs in this study are presented in Table 2. The index puncture force-elongation curves for GMBs 1 – 4 (Case 1: effect of GMB type) are shown in Figure 4.

Table 2: Index puncture force-elongation properties for the GMBs examined in this study (mean ± standard dev.)

		Yield		Peak		Puncture		Puncture Toughness	Elastic Modulus[3]
Name	Type	F (N)	δ (mm)	F (N)[1]	δ (mm)	F (N)	δ (mm)	N-m	N/mm
GMB1	1.5-mm HDPE	520 ± 6	6.4 ± 0.1	638 ± 7	17.6 ± 0.3	389 ± 10	27.0 ± 0.2	13.5 ± 0.3	96
GMB2	1.5-mm LLDPE	419 ± 6	6.9 ± 0.1	551 ± 15	16.6 ± 1.0	353 ± 25	29.9 ± 1.0	11.9 ± 0.8	78
GMB3	4-mm BGM[2]	-	-	445 ± 24	11.9 ± 0.4	-	-	2.8 ± 0.3	44
GMB4	2-mm text. HDPE	689 ± 29	7.6 ± 0.1	788 ± 25	13.6 ± 0.6	655 ± 92	18.8 ± 3.3	11.5 ± 2.6	120
GMB5	0.5-mm HDPE	200 ± 2	6.8 ± 0.2	297 ± 6	23.6 ± 1.2	154 ± 22	37.9 ± 2.3	8.3 ± 0.4	45
GMB6	1-mm HDPE	350 ± 2	6.7 ± 0.2	493 ± 6	21.8 ± 0.4	258 ± 24	33.9 ± 2.0	12.5 ± 0.5	70
GMB7	2-mm HDPE	671 ± 10	6.7 ± 0.1	774 ± 11	12.5 ± 0.2	373 ± 30	25.3 ± 0.7	14.2 ± 0.3	115

[1]The ASTM definition of "puncture resistance"
[2]Bituminous geomembranes (BGMs) do not show a separate yield point and the peak point = puncture point. This particular BGM did not contain a glass fleece and was from the lower end of BGM puncture resistance.
[3]Off-set tangent modulus of the elastic portion of puncture curve

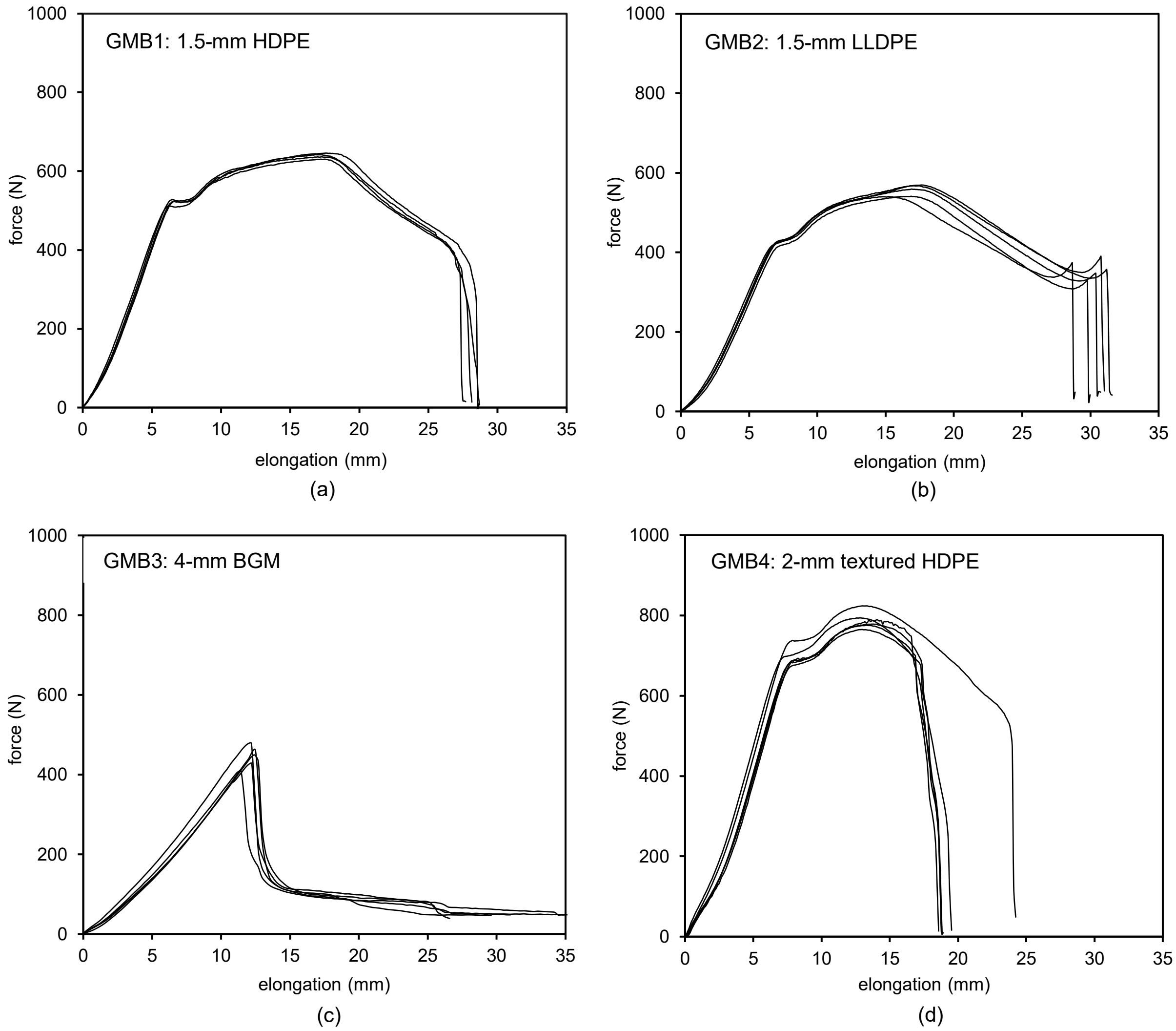


Figure 4: Puncture force-elongation curves for GMBs 1 – 4 (Case 1: Effect of GMB type). All plots are the same size and scale for comparison.

While the 1.5-mm HDPE GMB had higher force at all three points of interest (yield, peak, puncture) and higher off-set tangent modulus and puncture toughness than the 1.5-mm LLDPE, it had a lower elongation at yield and puncture (Figure 4a and b). The 4-mm BGM had a very different behavior having only point of interest; Peak (which equals puncture; Figure 4c). All of its measurable properties in the index test were the lowest of the GMBs examined with the exception of GMB5 (0.5-mm HDPE GMB) however, it should be noted that this particular BGM did not contain a fiberglass mat and had a middle to lower range puncture resistance compared to other BGMs from the same manufacturer. Recent testing at Queen's (unpub.) has revealed that BGMs have a wide range of puncture resistance depending on the type used (thickness) and if that type contains a fiberglass mat. It was not surprising that GMB4 (2-mm textured HDPE GMB)—being thicker than the 1.5-mm HDPE—had the highest peak force in this study (788 ± 25 N) however its post-peak break properties were highly variable; a result that is attributed to the textured asperities which cause premature rupture relative to the smooth edge of the roll.

The effect of changing the GMB thickness while keeping the GMB formulation constant (i.e., GMB5, GMB6, GMB7) showed—as one might expect—an increase in peak force with increasing thickness. Interestingly, this relationship was strongly linear with GMB thickness (Figure 5).

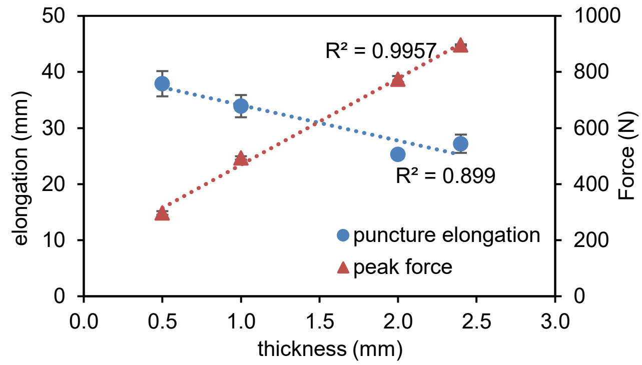


Figure 5: The index peak force and puncture elongation for different thicknesses of the same HDPE GMB formulation

3.2 *Performance test results*

The extent of puncture damage as measured by the number of holes in the performance test is presented in Table 3. The number of holes in each 0.59-m diameter test is presented along with that value scaled-up to holes per hectare. Although Case 2 used a lower stress, it was clearly the more aggressive case; This can be explained by the fact that the underliner in Case 2 (G3) was more poorly-graded than the underliner in Case 1 (G2).

Table 3: Performance test results

Name	Type	Test	Underliner	Overliner	Stress (MPa)	Damage holes	holes/ha
GMB1	1.5-mm HDPE	Case 1	G2	G1	2	5	1.8E+05
GMB2	1.5-mm LLDPE	Case 1	G2	G1	2	3	1.1E+05
GMB3	4-mm BGM	Case 1	G2	G1	2	66	2.4E+06
GMB4	2-mm text. HDPE	Case 1	G2	G1	2	0	0
GMB5	0.5-mm HDPE	Case 2	G3	G3	1.5	779	2.8E+07
GMB6	1.0-mm HDPE	Case 2	G3	G3	1.5	158	5.8E+06
GMB7	2.0-mm HDPE	Case 2	G3	G3	1.5	7	2.6E+05

4. DISCUSSION

4.1 *Index to performance test correlation: Case 1: Effect of GMB type*

The various properties obtained from the index puncture force-elongation curve were plotted against the number of punctures in the performance test for each GMB (Figure 6). The yield force showed a very poor correlation with holes (Figure 6a) and although yield elongation showed a better correlation, it was still misleading since it was not monotonic with the number of holes; In other words, one cannot discern if the trend is increasing or decreasing. The peak force (i.e., ASTM D4833 definition of puncture resistance) and the elongation at peak force also showed a non-monotonic and hence misleading correlation with the number of holes (Figure 6b). A similarly poor trend was also observed for the puncture toughness and off-set tangent modulus for the conditions examined (Figure 6c). On the other hand, the puncture break properties showed a monotonically increasing trend with the number of holes meaning they could potentially be useful (Figure 6d). The puncture force showed a decent correlation with the number of holes (R^2=0.94) while the puncture elongation (Figure 6d) showed an excellent correlation (R^2=0.99) for the conditions examined.

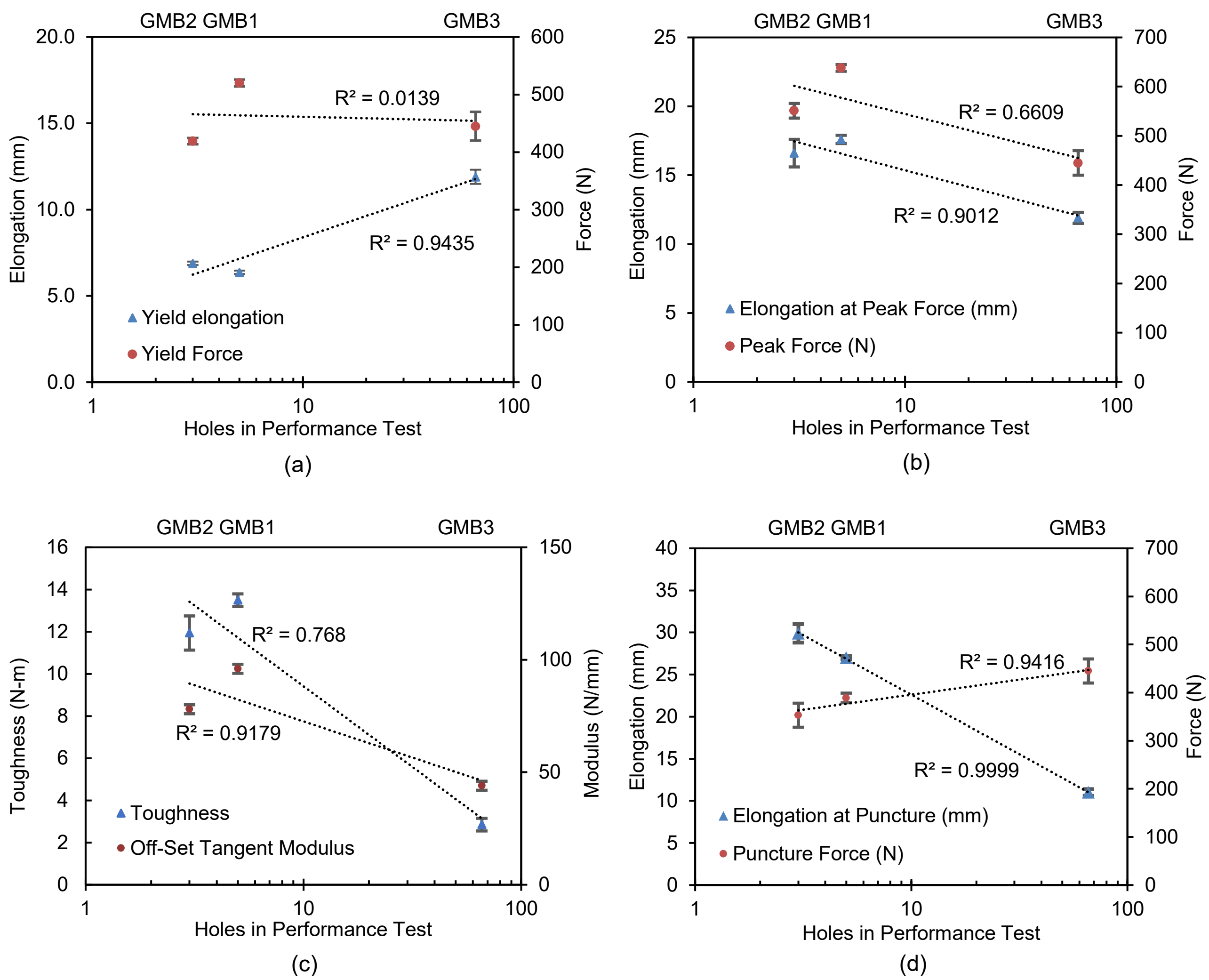


Figure 6: Comparison between index and performance puncture results for the Case 1 performance test (effect of GMB type). These GMBs include GMB1 (1.5-mm HDPE), GMB2 (1.5-LLDPE), GMB3 (4-mm BGM), and GMB4 (2-mm text. HDPE). GMB4 is not shown because it did not develop any holes.

Since GMB4 (2-mm textured HDPE) received no holes in the performance test, it could not be shown on the semi-log axis which requires a non-zero number. However—accepting that puncture elongation was a good predictor of holes—GMB4's puncture elongation of 18.8 ± 3.3 mm (from Table 2) should have resulted in around 15 holes using Figure 6d but there were actually zero holes. This indicates that using puncture elongation is not a perfect solution; In this case we cannot tell if it was due (1) the textured asperities which caused pre-mature rupture relative to the smooth edge of the roll, or (2) if it was due to GMB4 being thicker than the other PE GMBs examined since it was 2-mm instead of 1.5-mm thick.

4.2 *Index to performance test correlation: Case 2: Effect of HDPE GMB thickness*

To better isolate the effect of GMB thickness on puncture behavior, the correlation between index and performance puncture results for the Case 2 performance test series—which examined different thicknesses of the same HDPE GMB formulation—was evaluated (Figure 7). Investigating the effect of thickness was absolutely necessary since index testing revealed a trend of *increasing* puncture elongation with *decreasing* HDPE GMB thickness (refer to Figure 5) and this challenged the previous finding (that a higher puncture elongation gives less holes) since we know that thinner GMBs—all other things being equal—puncture more easily than thicker ones. Recall from Table 3 that the 2.0, 1.0, and 0.5-mm smooth HDPE GMBs examined received 7, 158, and 779 holes, respectively. Thus, for HDPE GMBs, it appears that the relationship between puncture resistance and thickness is exponential.

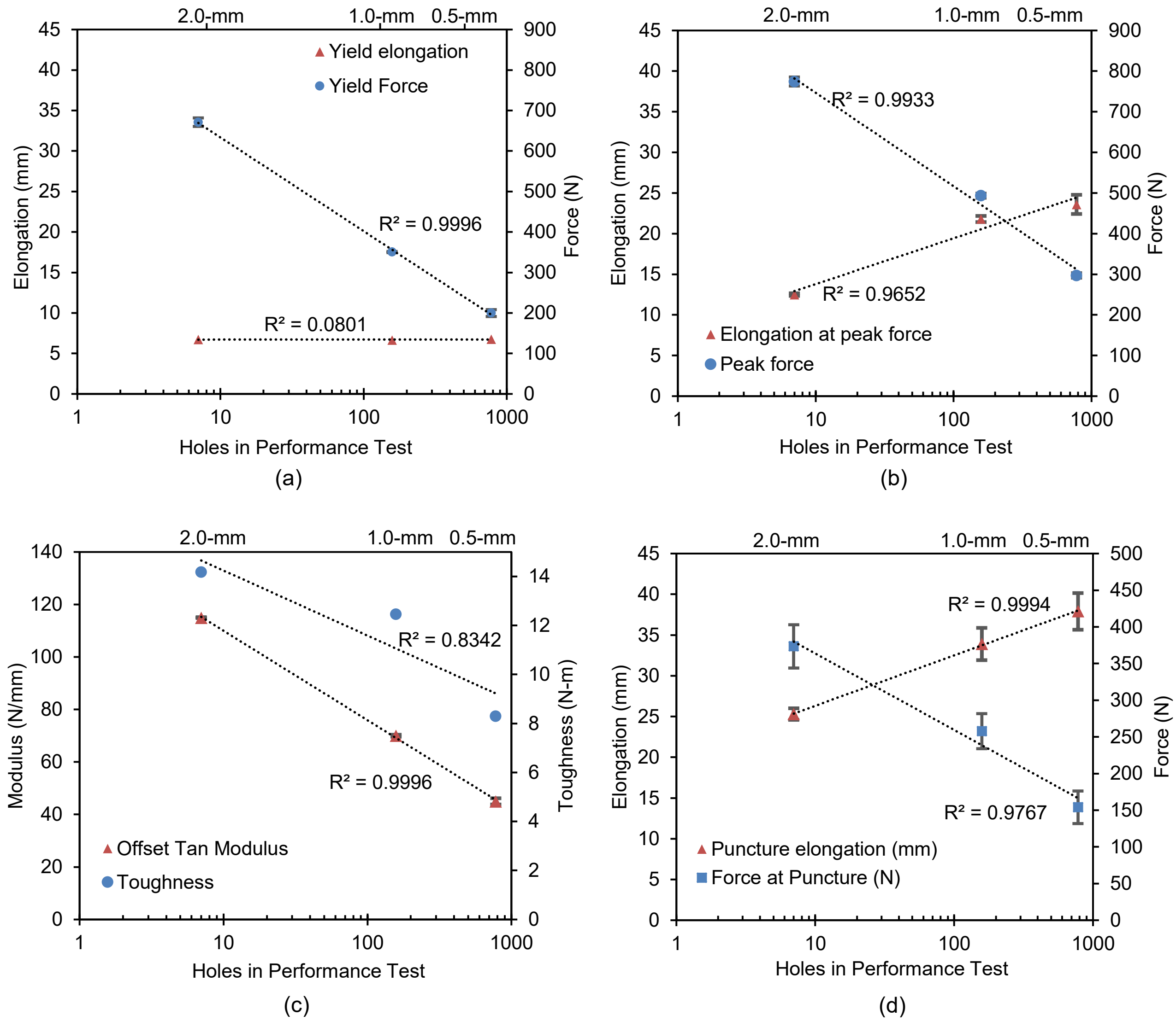


Figure 7: Comparison between index and performance test results for the Case 2 performance test (effect of GMB thickness). This includes GMB5 (0.5-mm HDPE), GMB6 (1.0-mm HDPE), and GMB7 (2.0-mm HDPE).

The correlation of yield properties to holes is shown in Figure 7a. The yield elongation did not change substantially with thickness and hence there is no useful correlation with the number of real holes, however, the yield force showed a very promising correlation. Unlike Case 1, the peak force (ASTM D4833 definition of puncture resistance) in this case showed a good correlation with holes (Figure 7b). Also unlike Case 1, the off-set tangent modulus in this case showed a good correlation with holes (Figure 7c) and it is not surprising that the correlation (R^2=0.9996) was the same as the yield force correlation (R^2=0.9996); They are both measuring the same thing since the yield strain did not change significantly with thickness. Lastly, the correlation of puncture break properties with holes is shown in Figure 7d. Similarly to Case 1, there was a strong correlation with puncture elongation, however, this time the trend was the opposite; The number of holes increased with increasing puncture elongation (instead of decreasing). This is likely to be confusing in practice therefore, when comparing different thicknesses of the same GMB, the peak force is a good indicator of puncture resistance.

4.3 *General discussion – Bituminous geomembrane (BGM) puncture*

The fact that the 4-mm BGM developed nearly 10-times more punctures than the 1.5-mm HDPE and LLDPE GMBs in the Case 1 performance test (heap leach pad) may come as a surprise to many readers however there are two things to consider. First, this loading condition was very aggressive (2 MPa, no protection layer) and this particular BGM was from the middle to lower end of available BGMs; It did not contain the fiberglass mat (fleece) that many BGMs have. Secondly, there are some types of geomembrane puncture tests where the BGM will appear to perform substantially better than most other GMBs. For example, the French standard NF-P84-510 (AFNOR 2002) and ASTM D5514-Procedure B both use leakage to define puncture resistance (typically taken as the hydrostatic water pressure at which a leak is detected). Thus, BGMs—which can form a tight seal around puncturing gravel particles (e.g., Clinton and Rowe 2017)—will tend to score much better than other GMBs in this kind of test simply because of the way puncture is defined in the test. Thus, the type of puncture test being used (or referenced) matters greatly for BGMs; arguably more so than with other types of GMBs. It is important to remember that puncture resistance in the liner load tests in this study was defined as the actual damage to the GMB by exhuming and inspecting the 0.59-m diameter samples. While the BGM's unique ability to form a gravel cake and seal around puncturing particles is promising, Clinton and Rowe (2017) have shown that preferential flow pathways can develop if the gravel crushes which is a stress and time dependent process. The BGM "sealing effect" and leakage behavior is presently the subject of on-going research at Queen's University.

5. CONCLUSION

This study evaluated correlations between the GMB index puncture resistance test (ASTM D4833) and a performance puncture test and also explored new ways of interpreting this common index test. Seven different GMBs were examined for their (1) index puncture and (2) performance test behavior which used a simulated deep burial, heap leach pad loading condition (high overburden stress and no GMB protection layer). For the conditions examined, the following conclusions were reached:

1. Although ASTM D4833 defines "puncture resistance" as the peak force on the force-elongation curve there are a total of eight (8) different properties one can readily obtain from this common index test when testing polymeric GMBs (yield force and elongation, peak force and elongation, puncture force and elongation, toughness, and off-set tangent modulus). Since bituminous geomembranes break at their peak and do not show a distinct yield point, they display four (4) reportable properties (peak force and elongation, toughness, and off-set tangent modulus).

2. For Case 1—which examined different GMBs (HDPE, LLDPE, BGM, textured HDPE) in the same aggressive deep burial simulation—the index puncture (break) elongation showed the strongest and most meaningful correlation to the number of holes while the other seven properties (including peak force) showed a misleading correlation with the number of holes. The exception was for GMB4 (textured 2-mm HDPE) which punctured prematurely in the index test (relative to the smooth edge of the roll) due to the textured asperities which create stress concentrations. The pre-maturely low puncture elongation for this GMB overpredicted the observed holes in the performance test; It suggested around 15 holes when there were actually zero. Although the smooth edge of the textured roll was not tested, its break properties (tensile and puncture) are likely representative of the GMBs true break properties.

3. For Case 2—which examined different thicknesses (0.5, 1.0, and 2.0-mm) of the same smooth HDPE GMB in an even more aggressive performance test—the number of holes increased exponentially with decreasing HDPE GMB thickness. The index puncture yield force, peak force, and off-set tangent modulus were all good indicators of actual puncture resistance. The puncture elongation also had a good correlation with holes however the trend was the opposite as Case 1; A high puncture elongation resulted in more holes here, not less. Since this is likely to cause confusion, the index peak force is the best indicator of puncture resistance when dealing with different thicknesses of the same HDPE GMB.

4. For the rather limited conditions examined, it appears that the index GMB strength (peak force) and extensibility (puncture elongation) are both important, however, deciding which is more important for a given scenario is still not entirely clear. The main finding from this study is to avoid making assumptions about GMB puncture resistance based on the index test ASTM D4833 because this value (in Newtons) can be misleading in some cases. This may explain why the European cousin of ASTM D4833 index test (EN ISO 12236 which also uses an 8-mm diameter puncture probe) reports ***both*** the peak force and deformation instead of just the peak force. Although more work is planned to further investigate this study, the index test will never be a substitute for performance testing with site-specific materials and anticipated stresses.

Limitations: This study only examined HDPE, LLDPE, and one type of BGM. The reader is reminded that these conclusions are preliminary and that additional work is planned. Furthermore, the conclusions are limited to geomembranes under very deep burial and in direct contact with coarse granular material. It is hypothesized that dynamic puncturing from equipment tire (or track) pressures over a thin gravel cover would depend more on GMB strength than extensibility. More research is needed to assess this condition.

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