High-pressure puncture testing of HDPE geomembranes

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ABSTRACT

Geomembranes are used to line the base of heap-leach pads used in copper and gold mineral extraction. Preliminary experimental results are reported to quantify the puncture resistance and short-term tensile strains induced in a 1.5-mm-thick high-density polyethylene geomembrane when buried beneath simulated heap leach materials and subjected to vertical pressures of 2000 kPa for 100 hours. For the particular materials tested, many holes were developed in the absence of any protection layer. A 540 g/m^2 nonwoven needle-punched geotextile protection layer was able to prevent short-term puncture of the geomembrane, but it was ineffective at limiting tensile strains as the short-term tensile strains exceeded the upper bound of proposed allowable limits by a factor of nearly 5.

RÉSUMÉ

Géomembranes sont utilisés pour la ligne de la base de tas-leach coussinets utilisés dans l'extraction minière d'or et de cuivre. Résultats expérimentaux préliminaires sont signalés à quantifier la résistance de la ponction et à court terme souches traction induites dans une géomembrane de polyéthylène haute densité de 1,5 mm d'épaisseur quand enfouis sous des tas simulées lixiviation de matériaux et soumis à des pressions verticales de 2000 kPa pour 100 heures. Pour les matériaux particulières testés, plusieurs trous ont été développés en l'absence d'une couche de protection. Une couche de protection géotextile non tissé aiguilletés de 540 g/m^2 a été en mesure d'empêcher une ponction à court terme de la géomembrane, mais il est inefficace à limiter les souches de traction comme les souches de traction à court terme a dépassé la limite supérieure des limites admissibles proposées par un facteur de près de 5 ans.

1 INTRODUCTION

Geomembranes are used to line bottom of heap leach pads used in copper and gold mineral extraction (e.g., see Thiel and Smith 2004, Lupo and Morrison 2007, Fourie et al. 2010, Lupo 2010). Heap leaching involves percolating a low or high pH solvent through piles of crushed ore. The solvent extracts the target mineral from the ore creating what is called the pregnant solution. The pregnant solution is collected at the base of the heap leach pad and then processed for mineral recovery. The purpose of the geomembrane is to increase the efficiency of pregnant solution collection and to protect the surrounding environment by minimizing fluid leakage through the bottom of the leach pad.

Fluid can pass through a geomembrane under a hydraulic gradient by leakage through holes in the geomembrane. The rate of leakage will depend on the number and size of holes, the permeability of the material beneath the geomembrane, the hydraulic gradient acting across the geomembrane and the contact conditions between the geomembrane and the underlying material (Rowe et al. 2004).

Holes or punctures can occur during installation (e.g., from improper handling of geomembrane rolls, dragging geomembrane panels over rough or rocky surfaces), from placement of overlying soil materials (e.g., dumping cover soil or possibly when there is only shallow cover soil and heavy construction equipment) and because of point loading from overlying or underlying gravel particles when subjected to the weight of the material on top of the geomembrane.

The number of holes caused during installation or by placement of overlying materials can be minimized by having effective construction quality control practices on site that should include qualified site inspection and leak detection surveys, where presumably most of these holes can be found and repaired prior to placement of the ore. The number of holes that may develop over time from the weight of overlying materials may be expected to depend on the grain size and distribution of both the material above and below the geomembrane, the stress acting on the liner, the type of geomembrane, the effectiveness of any protection layer and elapsed time.

Heap leach pads present challenging circumstances to assess and prevent geomembrane puncture because: i) coarse poorly-graded granular materials may be used above and below the geomembrane–denoted here as the overliner and underliner materials, respectively; and ii) the vertical stresses acting on the geomembrane may be enormous as heap-leach pads may be 50 to over 200 m deep (Thiel and Smith 2004, Lupo and Morrison 2007). As a result, there is a paucity of data on the puncture resistance of geomembranes in heap-leach pads where the stresses of 2000 kPa, and in some cases more, may be encountered.

The objective of this paper is to present the results from two preliminary experiments conducted to examine the physical performance of a 1.5-mm-thick high-density polyethylene geomembrane with coarse, poorly-graded granular materials above and below the geomembrane

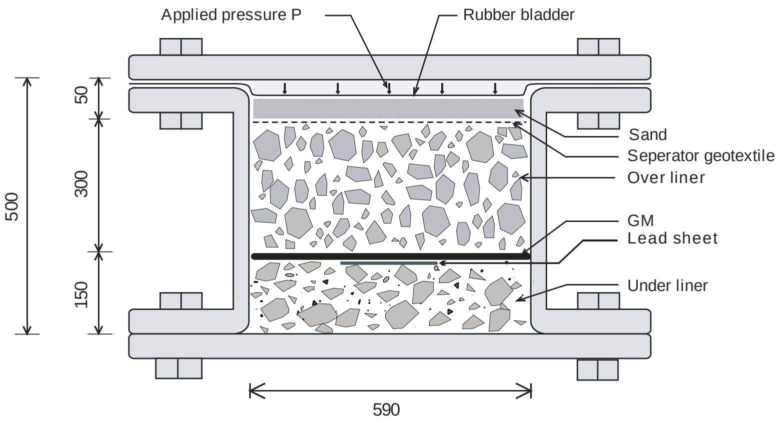

Figure 1. Cross-section through test apparatus showing configuration for test 1. Dimensions in mm.

and when subjected to an applied vertical pressure of 2000 kPa for 100 hours.

2 EXPERIMENTAL METHOD

2.1 Apparatus

A cylindrical steel pressure vessel with an inside diameter of 590 mm and a height of 500 mm and capable of applying vertical pressures of up to 3000 kPa, shown in Figure 1, was used to conduct the tests. Vertical pressure is applied by using fluid pressure acting on a flexible rubber bladder while horizontal pressures develop corresponding to conditions of zero lateral strain by limiting the outward deflection of the test apparatus. Friction on the vertical boundaries of the test apparatus is reduced to have less than a 5% impact on the vertical stresses acting on the geomembrane.

The pressure was applied in increments of 200 kPa every 10 minutes until a pressure of 2000 kPa was reached. It was then held constant for 100 hours. Temperature was maintained to 22 ± 1°C throughout the test.

2.2 Materials

Recognizing that the materials above and below the geomembrane in any heap each project will be site specific, the testing reported here may not necessarily be applicable for different conditions. The grain size envelope of overliner materials from several mining projects compiled by Lupo and Morrison (2007) was used as guidance to select the material placed above the geomembrane in these tests. As shown in Figure 2, the overliner material used in this preliminary study was selected to be towards the coarser limit of their envelope. The coarse particles were crushed from limestone that produced sub-angular with some sub-rounded particles. Material with the same gradation as the overliner but with added silty-sand such that 10% by mass was finer than 2 mm was placed beneath the geomembrane. Figure 3a is a photograph of the resulting surface just beneath the geomembrane where there were discernable voids in between the coarser particles. These conditions are expected to be more extreme than those described by Lupo and Morrison (2007). In test 2, silty-sand was used to fill in the voids between gravel particles in the top layer in contact with the geomembrane, as shown in Figure 3b.

Index tensile properties of the particular 1.5-mm-thick high-density polyethylene geomembrane tested are given

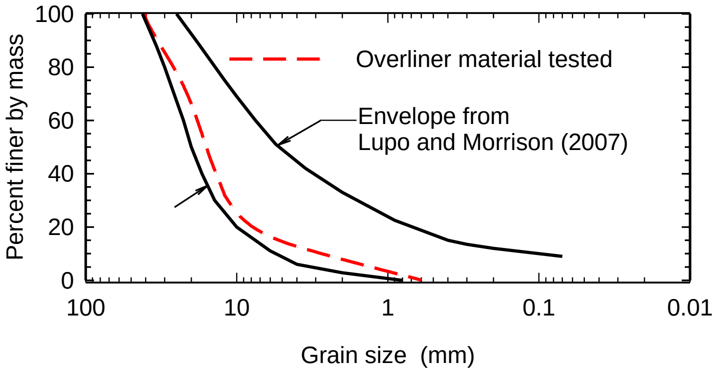

Figure 2. Grain size distribution curve of overliner material tested.

in Table 1. No protection layer was placed above or below the geomembrane in test 1 (Figure 1). A nonwoven needle-punched geotextile with mass per unit area of 540 g/m2 was placed directly above the geomembrane as a protection layer in test 2. In both tests, a 270-mm-square soft lead sheet (0.4 mm thick) was placed beneath the geomembrane to record its permanent deformations.

Figure 3. Photographs showing surface directly beneath the geomembrane prior to: a) test 1 and b) test 2.

Table 1. Index stress-strain properties (measured in the machine direction) of the 1.5-mm-thick HDPE geomembrane tested following ASTM D6693.

Property	Mean	Standard deviation
Yield strength (kN/m)	27	1
Break strength (kN/m)	46	5
Yield elongation strain (%)	24	2
Break elongation strain (%)	830	80

3 PRELIMINARY RESULTS

The results from test 1 – with no protection layer – are examined first. Photographs taken of the top and bottom surfaces of the geomembrane following test 1 are shown in Figures 4a and 4b, respectively. Nine punctures were found in the geomembrane and occurred at locations indicated by the red circles in Figure 4b. A puncture is defined here as a hole that had developed in the geomembrane from the short-term application of pressure. The nature of this preliminary test does not permit determination of the pressure or time puncture first occurred, but rather provides the punctures that were evident after 2000 kPa held for 100 hours.

Interestingly, all punctures occurred from gravel particles from the under liner. Close up pictures at three of the puncture locations are shown in Figures 4c-h. For reference, Figs 4c, 4e and 4g show the top surface of the geomembrane with the indentation coming out of the plane of the picture, while Figs 4d, 4f and 4h show the bottom surface of the geomembrane with the indentations going to the plane of the picture. For a sense of scale, diameter of the colored circles in Figure 4 is 19 mm.

Puncture 3 (Figs 4c-d) was caused by a 40-mm-long angular edge of a gravel particle in contact with the geomembrane producing a narrow 5-mm-high indentation. The puncture is not visible in the photographs because it was located on the side of the indentation towards the bottom of the indentation and had a diameter just less than 1 mm. Puncture 6 (Figs 4e-f) was caused by a sharp tip of a gravel particle resulting in a 5-mm-high indentation in the geomembrane. The hole here was small, approximately 0.1 mm wide and 0.5 mm long, and located at the centre of the indentation. Puncture 7 was also caused by a 40-mm-long angular edge of a gravel particle and was very small with a diameter less than 0.5 mm.

All indentations that lead to punctures also had significant tears on the top surface of the geomembrane. For example, Figure 4c shows a tear that was approximately 10 mm long and 1 mm deep towards the bottom of the indentation. These are termed as tears, rather than cracks, since cracking has connotations with brittle stress cracking behavior. Further, there were around 130 gravel contacts on the test specimen where tears had developed on the top surface of the geomembrane, but there was no formation of a hole in the short-term test. For example, Figure 5 shows a location with 0.5-mm-deep tears. While these tears are not features for hydraulic flow in the short-term duration of the test, there is no data to suggest that this tear would not act like a stress concentration and in the longer term lead to formation of a larger hole in the geomembrane. Longer-term testing is currently underway to assess the potential implications of these tears.

Eight out of the nine punctures occurred at locations away from lead sheet, see Figure 4b. Only one developed in the geomembrane above the lead sheet although there were just as many deep indentations and significant tears above the lead sheet than away from it. Thus, it appears that the lead sheet may have prevented puncture, and thus the number of punctures in the test was likely underestimated. The intent of the lead sheet was to capture the deformed shape of the indentations to then permit computation of strain. Brachman and Gudina (2008) showed that the lead sheet had no discernable impact on the local deformations and hence computed tensile strains in the geomembrane at applied stresses of 250 kPa. It appears that if the objective of the test is to quantify tensile strains prior to rupture, then inclusion of a lead sheet beneath the geomembrane is necessary and may be acceptable; however, if the objective is to

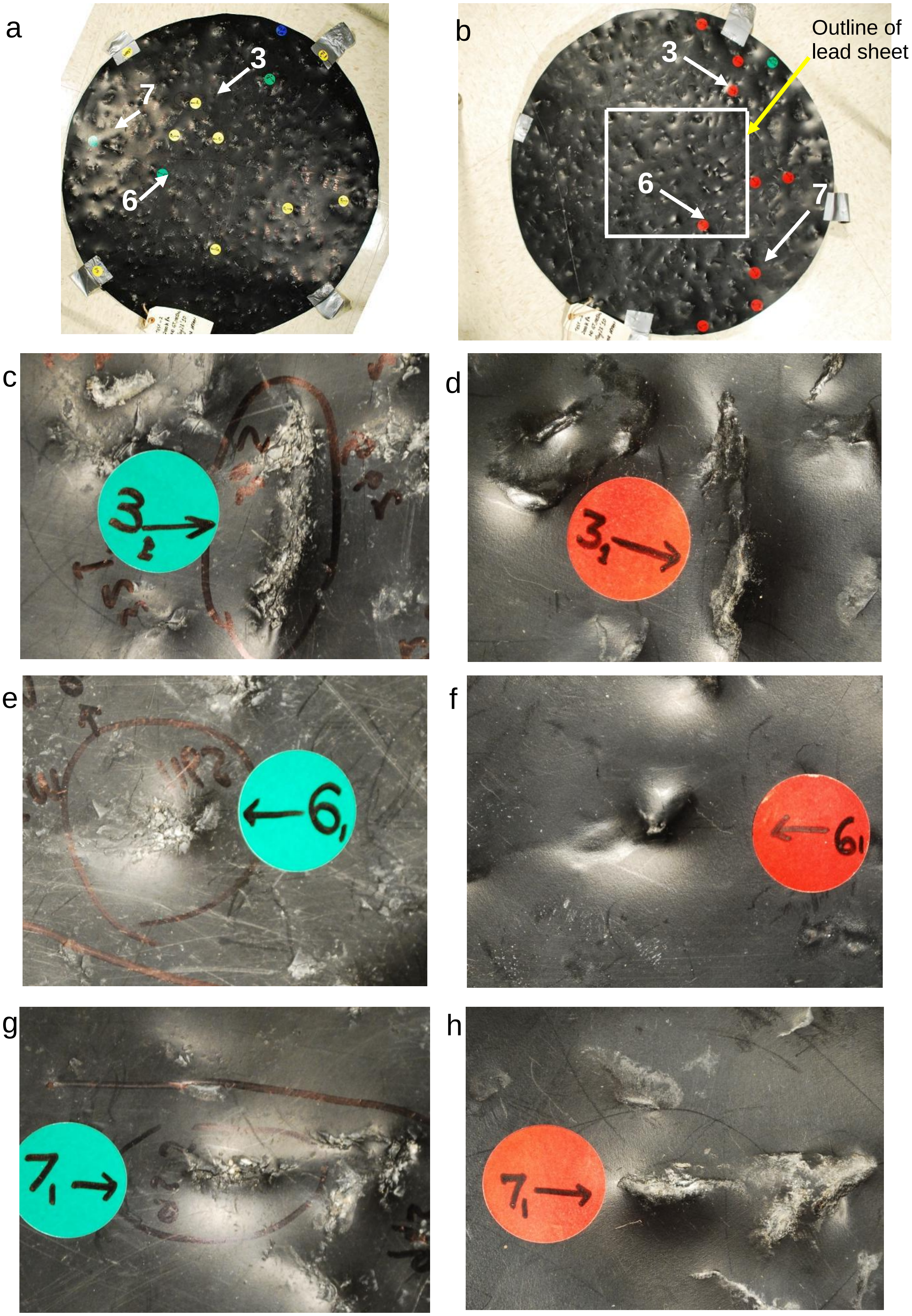

Figure 4. Photographs of geomembrane following test 1.

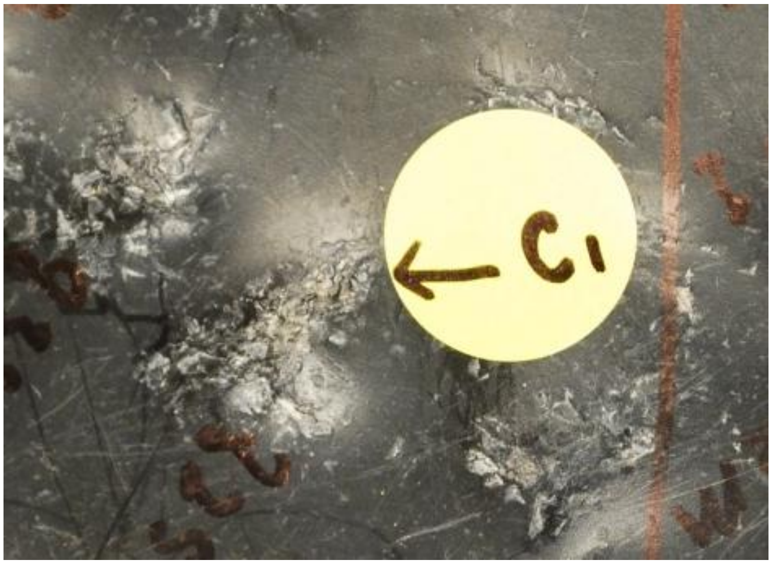

Figure 5. Photograph of tears on the top of the geomembrane following test 1.

establish how many punctures and at what pressure or time they may occur, then it may not be appropriate to include the lead sheet. Future testing will be conducted to assess the extent to which the lead sheet influences puncture.

Results from test 2 were quite different, as no short-term puncture occurred. Test 2 differed from test 1 in two ways: i) silty-sand was used to fill in the voids between gravel particles in the top layer of the under liner that was in contact with the geomembrane, and ii) a nonwoven geotextile was placed on top of the geomembrane. Future testing will be conducted to better quantify the affects of the underliner gradation and any protection layer on top of the geomembrane. Although no short-term geomembrane puncture in test 2, there were still five noticeable permanent indentations in the geomembrane that showed signs of small surface tears.

In addition to assessing whether there was short-term puncture of the geomembrane, these two tests provide an opportunity to evaluate the tensile strains in the geomembrane. Examining tensile strains may provide greater insight into the potential longer term performance of the geomembrane. The strains in the geomembrane were then calculated from the measured indentations in the lead sheet using the method developed by Tognon et al. (2000). This approach, while an improvement on simpler arc elongation methods, does assume small displacements to compute strains and as such will overestimate the actual tensile strains in the geomembrane. As a first approach, it also neglects any strain localization from the presence of tears. Indentation depth and width alone are not sufficient to capture the largest strain in a particle test, as the shape of the indentation is also important (Brachman and Gudina 2008). The process used here was to analyze ten prominent indentations recorded in the lead sheet thereby providing a good chance of capturing the maximum strain in any particular test.

The deformed shape of one particular indentation is shown in Figure 6a. This is the indentation at puncture location 6 from test 1. For reference, h is the height of the indentation measured from the deepest or highest (in this case highest) point of the indentation. Figure 6b shows the computed tensile strains for this indentation, with tensile strains plotted as positive. Tensile strains of the order of 20 to 30% were calculated. Clearly if puncture strain is around 20 to 30%, the break elongation strain of over 800% (and even yield elongation strain of 24%) from ASTM D6693 index dog-bone tension testing (Table 1) bears little resemblance to behavior measured in the performance testing. The five largest tensile strains calculated from tests 1 and 2 are given Table 2. As expected, on average the tensile strains are larger in test 1 than in test 2; however, the largest strain in each test are nearly the same. The strain of 38% in test 2 occurred at a significant indentation where there was no puncture, but evidence of tears on the top surface of the geomembrane. Obtaining one large value of strain in test 2 highlights the need to conduct sufficient replicate tests prior to making an engineering decision on geomembrane protection.

Although further testing is required to characterize the tensile strains that may develop, it is interesting to compare the strains in Table 2 with available strain limits. Although there is no generally accepted allowable long-term strain for HDPE geomembranes, Seeger and Müller (2003) have proposed a limit of 3% while Peggs el al. (2005) proposed a limit of 6 to 8%, depending on the its initial stress crack resistance. Even in test 2, there are many locations where calculated short-term tensile strains exceed proposed long-term strain limits.

There is need for discussion amongst stakeholders of these sorts of heap leach applications as to the potential implications of these large tensile strains. Arguments can be made that stress relaxation will reduce the tensile stresses associated with these indentations, and thereby, there will be no rupture by environmental stress cracking.

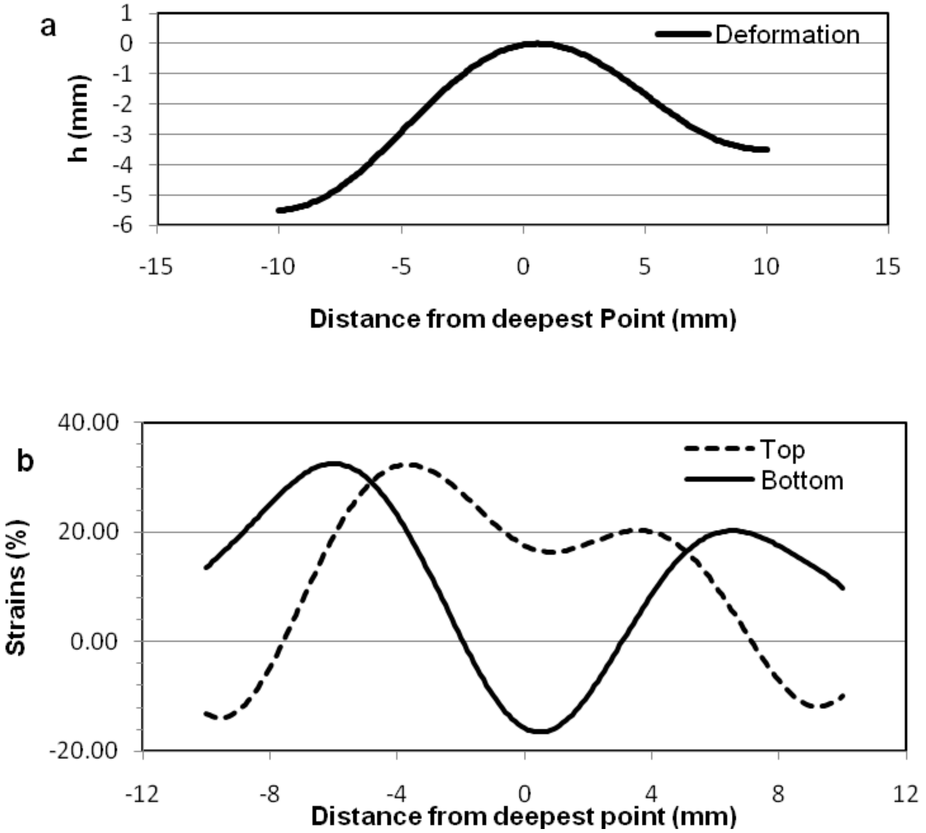

Figure 6. a) Deformed shape and b) calculated strain for an indentation from test 1.

However, despite relaxation of tensile stresses, tensile strains remain and with small long-term creep displacements of materials beneath the geomembrane, there may be propagation of a crack in a geomembrane indentation such that it can rupture and form a hole even though it was subjected to constant applied force (Sabir 2010). It is suggested here that it is not necessarily sufficient to conduct short-term tests to assess whether or not there is short-term puncture of the geomembrane and that some consideration be given for limiting tensions in the geomembrane when designing a protection layer from materials above and below the geomembrane. Selection of this limit should involve considerations of what is an acceptable leakage rate and the time frames involved.

Table 2. Calculated tensile strains (%) for five prominent indentations in the geomembrane.

Test 1	Test 2
41	38
34	18
33	17
28	14
27	10

4 SUMMARY

Results were presented from two preliminary experiments to examine the physical performance of a 1.5-mm-thick high-density polyethylene geomembrane with coarse, poorly-graded granular materials above and below the geomembrane and when subjected to an applied vertical pressure of 2000 kPa for 100 hours.

In one test with no protection layer above or below the geomembrane, there were nine punctures that developed in the test specimen. This corresponds to over 300,000 holes per hectare. Further, there were many more locations where the geomembrane was not punctured, but there were noticeable tears in the geomembranes. In the other test with a nonwoven protection geotextile above the geomembrane and a silty-sand infill protection layer beneath the geomembrane, there was no short-term puncture; however, the largest tensile strains exceeded even the upper bound of proposed tensile strain limits by a factor of almost 5.

Further testing is required to quantify the performance of geomembranes under large pressures for heap leach applications. The results reported apply only for the specific test conditions involving short-term physical loading sustained for 100 hours at a temperature of 22°C and as such will underestimate the strains expected under long-term conditions such as exposure to chemicals and elevated temperature conditions prevailing over extended periods of time.

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