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Effect of underliner on geomembrane strains in heap leach applications☆

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ABSTRACT

A review of 92 heap leach projects from 15 countries provides a starting point for a series of experiments, at 22 °C and a vertical pressure of 2000 kPa, to examine short-term puncturing and the development of geomembrane strains that could affect longer-term performance. Underliners of gravel with some sand or those of gravel and sand caused significant puncturing and excessive strains in the geomembrane for the conditions examined. The shape of the underliner grading curve had a much greater effect on the potential for puncturing and the magnitude of the strains in the geomembrane than just the maximum particle size. Of the six granular underliners examined, the best performance was for the well graded gravelly sand with some silt which offered sufficient support to minimize the strains in the geomembrane due to the overliner while not inducing significant strains directly from the underliner. Nevertheless even in this case the maximum strain of 11% is almost double the maximum recommended in the literature for ensuring good long-term performance of the geomembrane. Consideration of composite liners with GCLs and compacted clay liners shows that the more deformable the foundation, the larger are the indentations and strains induced in the geomembrane by a given overliner. For the specific conditions examined, it is shown that there was no apparent improvement in performance for an LLDPE geomembrane versus the HDPE geomembrane tested. A 540 g/m^2 geotextile protection layer above the geomembrane was also found to be insufficient to prevent significant strains in the geomembrane due to the overliner examined.

1. Introduction

Heap leaching has gained wide acceptance as a relatively low cost method for the recovery of metals (Smith, 2004). The mined ore is crushed and placed in 5–10 m thick lifts over a geomembrane lined pad (Breitenbach, 2005). A chemical solution, with the characteristics appropriate to leaching the mineral to be extracted, is applied at a controlled rate to the ore, most commonly via a drip irrigation system. As the solution percolates through the ore it dissolves the metal of interest, producing a solution referred to as the 'pregnant liquor' or 'pregnant leach solution' (PLS). This solution is collected at the base of the heap leach pad and directed to a recovery plant for metal recovery (Fourie et al., 2010).

The geomembrane liner serves to minimize the loss of the PLS (and hence valuable minerals as well as the process reagents) but also minimizes environmental impact due to the escape of PLS. Geomembranes provide an excellent barrier to the PLS except where there are holes (Rowe, 2012). Thus it is desirable to minimize the number of holes throughout the period when the PLS will be captured for mineral recovery and potentially for a longer period during which the escape of fluids leached from the ore could have a negative impact on the environment.

Heap leach pads represent a challenging environment for any liner. The challenges include high stresses with ore heights reaching 240 m, and stresses of up to 4000 kPa on the liner, having been reported (Lupo, 2010). Additional factors that could affect liner performance include the presence of a coarse overliner, gravel in the underliner, very high or low pH leach solution (Abdelaal et al.,

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2011, 2012), hydraulic heads of up to 60 m, and potentially high temperatures (e.g., Thiel and Smith, 2004). Lupo and Morrison (2007) developed general guidelines for geomembrane selection based on the applied load, characteristics of the foundation, overliner materials, and liner bedding materials. However, specific testing should be conducted to assess geomembrane liner performance for the given site conditions.

The cylinder test method (as described in Environmental Agency, 2006; Shercliff, 1998; Brachman et al. 2000; Thiel and Smith, 2004; Lupo and Morrison, 2007) is one technique used to assess the potential for geomembrane puncture for a given underliner and overliner. In these high-load static puncture tests, the proposed underliner and overliner materials are placed below and above the geomembrane of interest and subjected to applied pressures up to 2000 kPa (Thiel and Smith, 2004). These tests focus on puncture due to vertical load. They do not represent lateral or horizontal loading that may be induced due to stacking equipment, angle of repose face angles of the first ore lift, or the relatively steep liner grades present on some pads. Because of the horizontal loading (and strain) one may also examine the condition of liner samples coming out of a large direct shear test as representing a limiting condition for horizontal loading. Both the cylinder and the direct shear tests provide information about potential short-term puncture at the temperature at which the test is performed. While it is certainly necessary to avoid short-term puncture, the absence of puncture does not mean that holes will not develop with time in areas where there are high tensile strains (Seeger and Muller, 2003; Peggs et al., 2005). Yet there is a paucity of archival literature dealing with strains in geomembranes used in heap leach applications.

The objectives of this paper are to: (a) identify common features of heap leach pads, (b) examine the effect of the underliner on puncture and short-term tensile strains induced in 1.5 mm thick HDPE geomembrane, and (c) examine the relative performance of 1.5 mm thick HDPE and LLDPE geomembranes under similar conditions.

2. Characteristics of heap leach pads

The unit weight of the ore in a heap leach pad depends on a number of factors with typical moist values reported to range from 17.3 kN/m^3 (110 pcf) to 20.4 kN/m^3 (130 pcf) with the maximum unit weight occurring during leaching (Breitenbach and Thiel, 2005). The present study included a review of 92 heap leach projects from 15 countries (Argentina, Brazil, Chile, Colombia, Ghana, Indonesia, Mexico, Namibia, Niger, Peru, Philippines, Poland, Turkey, USA, and Uzbekistan) to identify common features. Data were available regarding the height of ore at 72 of the projects examined (Fig. 1). Approximately 51% of cases had ore heights of 50 m or less (i.e., typically less than about 1000 kPa of vertical pressure), 90% were 100 m or less (≤2000 kPa), but 10% were 150 m or higher (≥2600 kPa) with a maximum height of 238 m (≤4800 kPa). Based on this information, the experiments conducted in this study were for a pressure of 2000 kPa (i.e., covering 92% of the cases).

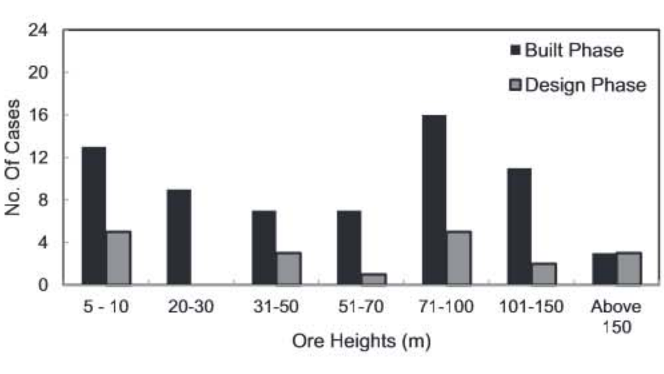

Fig. 1. Histogram of heap leach ore height for 72 cases where data was available.

2.1. Underliner material

Lupo and Morrison (2007) indicated that, where possible, a native soil is used as the underliner to minimize construction costs. They indicated that typically requirements for the underliner include a non-gap graded particle distribution, a maximum particle size of 38 mm, greater than 15% fines (i.e. <0.075 mm), a plasticity index greater than 15%, and a saturated hydraulic conductivity of less than 1 × 10^{-8} m/s. Lupo and Morrison (2007) presented a grain size envelope of underliner materials from several mining projects as defined by the curves UL2 and UL6 in Fig. 2. Of the 92 cases reviewed as part of the current study, the underliner was described as clay in 48% of cases (although clay should probably be interpreted as soil with significant fines and these fines may not actually include significant clay in some cases), native soil in 9%, a GCL in 5%, tailings in 4%, silt/sand in 3%, and was not given in 30% of cases.

2.2. Geomembrane

The literature indicates that the most common geomembrane used for a leach pad liner is 1.5 mm polyethylene (either HDPE and LLDPE) but that thicker PE is used occasionally for deeper heaps and 0.75–1.0 mm PVC has been occasionally used (Thiel and Smith, 2004; Lupo, 2008). Data on the liner were available for 88 of the 92 cases examined in this study. This data indicated that HDPE was used in 75% of cases (presumably because of its good chemical resistance), LLDPE in 22% of cases, and PVC in only 3% of cases. Although LLDPE only represented 22% of cases examined in total, there appeared to be a trend of increasing popularity of LLDPE in the more recent cases and for heap pads in the design phases LLDPE was being considered in about 50% of cases.

The thickness of geomembrane used was 1 mm in only 5% of cases, with PVC being used for heaps less than 20 m and HDPE for heaps less than 50 m. A thickness of 1.5 mm was used in 46% of cases (40% HDPE, 6% LLDPE) with a maximum heap height of 120 m for HDPE and 90 m for LLDPE. A thickness of 2 mm was used in 45% of cases (31% HDPE, 14% LLDPE) with the HDPE being used for heap heights up to 238 m and LLDPE up to 160 m. The 2.5 mm

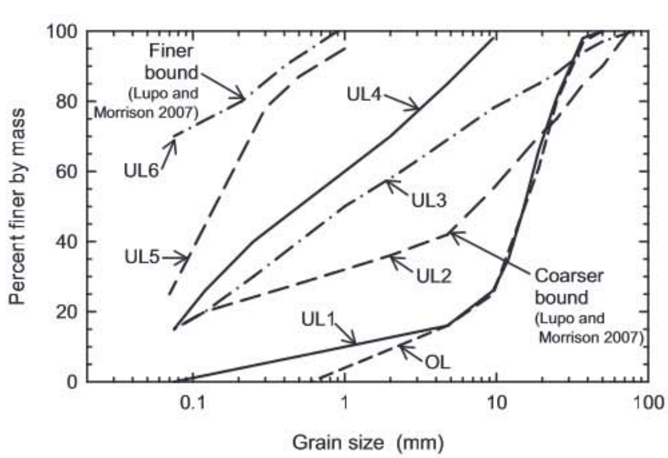

Fig. 2. Grain size distribution of underliners (UL1–UL6) and overliner examined (OL) in this study and bounds of underliner in projects reported by Lupo and Morrison (2007).

geomembrane was only used in four cases (4%); 2 involved HDPE and heaps of 140 and 180 m in height while LLDPE was used in two cases with heaps of 160 m. Thus the review of the cases examined in this study indicates that 1.5 mm HDPE is the most commonly used geomembrane and 2 mm HDPE the next most common (they represent 71% of cases).

2.3. Overliner material

The overliner above the geomembrane serves a number of purposes including contributing to the drainage of the PLS to a collection point. The collection of the PLS is enhanced by the use of geopipes. Typical diameters for geopipes include 100, 150, and 180 mm (Thiel and Smith, 2004) and they are generally spaced 2–10 m apart based on the authors' experience. This is somewhat wider than reported by Fourie et al. (2010). This drainage layer is also comprised of gravel or coarse-grained sand with a gradation as needed to achieve the design hydraulic conductivity and shear strength under the maximum ore load while providing adequate puncture protection. In addition, the overliner needs to be selected such that it prevents damage to the underlying geomembrane. Ideally, a single layer will meet both objectives. However, in some cases the properties of the drainage layer may be such that it would damage the geomembrane and in these cases the overliner layer above the geomembrane may include a protection layer to separate the drainage layer from the geomembrane. When used, the protection layer may be a sand and gravel mixture, silty soil, or clayey soil (Lupo and Morrison, 2007). However, geotextile protection layers are not commonly used in heap leach pads because of issues related to the high costs associated with construction of this layer over the large pad areas (150–200 ha) and concerns about stability given the very high fills, angle of repose lift slopes, relatively steep overall slopes, elevated phreatic surfaces, relatively high levels of saturation above the phreatic surface, and very high seismicity in some areas.

Typically, the drainage layer will have a minimum desired saturated hydraulic conductivity of 1×10^{-4} m/s with well-graded rounded gravel or coarse sand being preferred (Lupo, 2005), although values of 5×10^{-5} m/s are common in practice. The properties of the overliner materials were only reported for 15 of the cases examined in this study. The overliner had a maximum size of 12 mm (0.5″) in 20%, 19 mm (0.75″) in 53%, 25 mm (1″) in 13%, and 38 mm (1.5″) in 13% of these cases. The overliner thickness was reported for 52 cases examined in this study. Most commonly (29% of cases) it was 300 mm thick. However thickness varied substantially. The overliner thickness was ≤400 mm in 40% of cases, 500–600 mm in 27% of cases, 700–1000 mm in 10% of cases, and 2000–2500 mm in 23% of cases. These larger thicknesses are for dynamic or "on/off" pads where the stacking and off-loading equipment works directly over the overliner and the loading is repeated up to several times a year for possibly 20 or more years. For on/off pads 1000 mm tends to be the minimum overliner thickness and 2000 mm is relatively common when large mine haul trucks are used to haul the ore onto the pad and then large rubber-tired loaders (such as Cat 992) are used to stack the ore.

3. Experimental method

3.1. Test apparatus

The experiments forming the present study were conducted in a cylindrical steel pressure vessel with an inside diameter of 590 mm and height of 500 mm (Fig. 3). A vertical pressure of up to 3100 kPa can be applied by fluid pressure acting on a flexible rubber bladder. The horizontal pressures developed correspond to essentially zero lateral strain due to the limit on the outward deflection provided by the very stiff steel cell (Brachman and Gudina, 2002; Krushelnitzky and Brachman, 2009). Friction along the cell walls was minimized using two layers of 0.1-mm-thick polyethylene (PE) sheet with high-temperature bearing grease between the PE sheets. One PE layer was attached to the wall of the test apparatus while the other, moved with the overliner material. The friction treatment was protected by a series of 45-mm-wide HDPE sheets arranged in rings with a vertical spacing of 5 mm between the rings. This friction treatment has been shown to reduce the boundary friction to less than 5° (Tognon et al., 1999). With this treatment, in excess of 95% of the vertical stress has been shown to be transferred to the geomembrane (Brachman and Gudina, 2002).

3.2. Underliners considered

Table 1 summarizes all the experiments discussed in this paper. Six underliners denoted UL1–UL6 (Fig. 2) were examined with the choice being guided by the information on underliners gained from the projects considered in this study (discussed earlier) as well as the grain size envelope of underliner materials compiled from several mining projects by Lupo and Morrison (2007). In each case, particles coarser than 0.6 mm were sub-angular and angular. The grading curves of the underliners are described below. The as-placed and final water content and dry densities of the

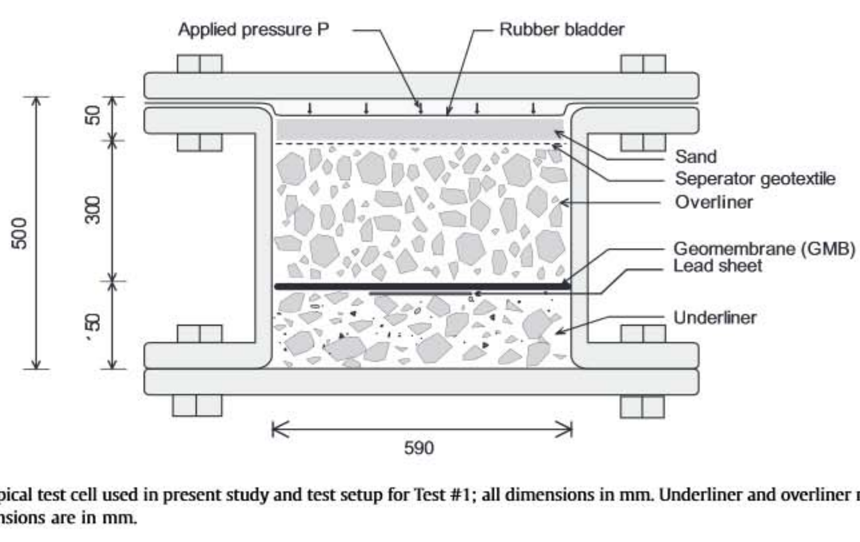

Fig. 3. Cross section through a typical test cell used in present study and test setup for Test #1; all dimensions in mm. Underliner and overliner material shown schematically only and not drawn to scale. All dimensions are in mm.

Table 1
Summary of the 19 experiments conducted at 22 °C and an applied pressure of 2000 kPa. All experiments except Test 2A were for a 1.5 mm HDPE geomembrane. Test 2A was for a 1.5 mm LLDPE geomembrane.

Test	Underliner designation	Underliner description
1	UL1	Gravel, some sand
1A	UL1[a]	
2	UL2	Gravel and sand
2A		
3	UL3	Sand and gravel, some silt
3A		
4	UL4	Gravely sand, some silt
5	UL5	Silty sand
5A		
5B		
6	UL6	Sandy silt
7	GCL hydrated at 20 kPa	Silty sand
7A		
8	GCL hydrated at 2000 kPa	Silty sand
8 A		
9	Clay @ 12% w	Clay
9A		
10	Clay @ 16% w	Clay
10A		

Underliner description is based on classification given in Canadian Foundation Engineering Manual (2006).
[a] A thin layer of silty sand was placed over the gravel.

underliners are given in Table 2. Table 3 gives the values of D_{20}, D_{40}, D_{60}, D_{80} and D_{100} and a parameter defined as the slope index, s_{x-y} (which gives the relative slope of the grading curve in Fig. 2 between two particle sizes x and y (e.g., between D_{100} and D_{80} $s_{100-80} = 1/(\log_{10} D_{100} - \log_{10} D_{80})$) for each underliner material.

Underliner UL1, used in Tests 1 and 1A, had a maximum particle size of 38 mm and negligible fines (Figs. 2 and 4a). Except for the particles less than D_{15} (which were smaller than for the overliner) this underliner was essentially the same as the overliner. It was selected to assess whether puncturing of the geomembrane would occur under these conditions. In Test 1A, additional silty-sand was used to fill in the voids between gravel particles in the top layer in contact with the geomembrane. Tests 2 and 2A used an underliner with grading curve UL2 (Figs. 2 and 4b) which was selected to be

Table 2
Properties of underliners considered.

Test	Underliner	Initial water content (ω)%	Final water content (ω)%	Initial dry density ρ_{dry} (kg/m^3)	Final dry density ρ_{dry} (kg/m^3)
1	UL1	0.2	0.25	1860	1990
1A	UL1*	0.5	0.5	1860	1990
2	UL2	3	3	1750	1870
2A		3.3	3.2	1740	1860
3	UL3	12.8	12.5	1730	1930
3A		12.4	12	1760	1880
4	UL4	12	11.5	1760	1880
5	UL5	11.6	10.8	1740	1810
5A		15.6	13.8	1760	1880
5B		12.0	11.2	1760	1840
6	UL6	11.5	10.6	1730	1790
7	GCL	85.0	65.6	–	–
7A	hydrated at 20 kPa	86.5	62	–	–
8	GCL	7.4	55	–	–
8 A	hydrated at 2000 kPa	7.0	54.8	–	–
9	Clay @ 12% w	12.2	10.8	1900	1980
9A		12.3	10.6	1900	2000
10	Clay @ 16% w	15.9	12.3	1900	2070
10A		16.3	12.5	1900	2090

Table 3
Grain size properties of underliner materials.

UL	D_{20} (mm)	D_{40} (mm)	D_{60} (mm)	D_{80} (mm)	D_{100} (mm)	Grading curve slope index			
						s_{100-80}	s_{80-60}	s_{80-60}	s_{40-20}
UL1	7	10.1	19	20.1	38	3.6	41	3.6	6.3
UL2	0.11	3.7	10.7	30	80	2.3	2.2	2.2	0.7
UL3	0.11	0.5	2.1	10.0	80	1.1	1.5	1.6	1.5
UL4	0.09	0.23	1	3.05	10	1.9	2.1	1.6	2.5
UL5	0.075	0.1	0.18	0.3	2	1.2	4.5	3.9	8.0

Slope index: = indicates relative slope of the grading curve in Fig. 2 between two particle sizes (e.g., between D_{100} and D_{80}: $s_{100-80} = 1/(\log_{10} D_{100} - \log_{10} D_{80})$).

the coarser bound of the cases examined by Lupo and Morrison (2007). This material had a larger maximum particle size (80 mm) than UL1 (38 mm) but had 15% fines.

Underliner UL3 (Tests 3 and 3A; Figs. 2 and 4c) had the same 80 mm maximum particle size and the same 15% fines as UL2, but the distribution of particles for UL3 was very well graded as compared to UL2 which exhibits a sharp change in the slope of the grading curve at about D_{40} (Table 3 and Fig. 2). Thus a comparison of results from Test 2 with those from Test 3 will allow an assessment of the effect of the sand and gravel grain size distribution between the same two limits.

Underliner UL4 (Test 4; Figs. 2 and 4d) was well graded like UL3 and had the same 15% fines, but had a smaller maximum particle size of 10 mm. Thus a comparison of the results from Tests 3 and 3A with Test 4 allows an assessment of the effect of the maximum particle size (80 mm versus 10 mm) for a well graded material with similar fines.

Underliner UL5 (Tests 5, 5A and 5B; Figs. 2 and 4e) was a silty sand with a maximum particle size of 2.0 mm and 25% fines.

Underliner UL6 (Test 6; Figs. 2 and 4f) was well graded with a maximum particle size of 0.9 mm and 70% fines. It corresponds to the finer bound of the cases examined by Lupo and Morrison (2007).

Test series 7 and 8 involved a composite liner with the geomembrane over a geosynthetic clay liner (GCL) which was underlain by silty sand (UL5) foundation layer. The silty sand was compacted using standard Proctor energy to a maximum dry density of 1750 kg/m^3 at standard Proctor optimum moisture content of 11.4% (dry weight basis). The GCL (Bentofix NSL manufactured by TAG Environmental Inc., Barrie Ontario, Canada) had a minimum average roll value (MARV) bentonite mass per unit area (M_A) of 3660 g/m^2 and was needle-punched with a woven carrier geotextile (MARV $M_A = 105$ g/m^2). The needle-punched fibers were thermally fused to the carrier geotextile. The GCL was installed with the nonwoven cover geotextile in contact with the geomembrane (i.e., with the woven carrier geotextile on the silty sand).

Test series 7 and 8 differed in terms of the manner in which the GCL was hydrated. For Test series 7, the GCL was hydrated for 7 days under a confining stress of 20 kPa. This resulted in an initial gravimetric water content of 86 ± 1%. For Test series 8, the GCL was placed on the silty sand foundation prepared as it was for Test series 7 (i.e., at optimum moisture content of 11.4%) but the moisture content of the underlying soil was increased to 20% (field capacity) by adding water to the subgrade before placing the GCL. The off-the-roll gravimetric water content of GCL was 7%. The GCL was hydrated from the foundation layer during the test in the cell at a pressure of 2000 kPa. The thicknesses of GCL before and after each test (obtained using the measurement technique developed by Dickinson and Brachman, 2006) are reported in Table 4.

Test series 9 and 10 involved a composite liner with the geomembrane over a compacted clay liner. The clay was Halton Till and had a liquid limit of 26%, plastic limit of 16% and 32% clay size (≤2 μm). For standard Proctor compaction, the clay had a maximum dry density of 1900 kg/m^3 at an optimum water content

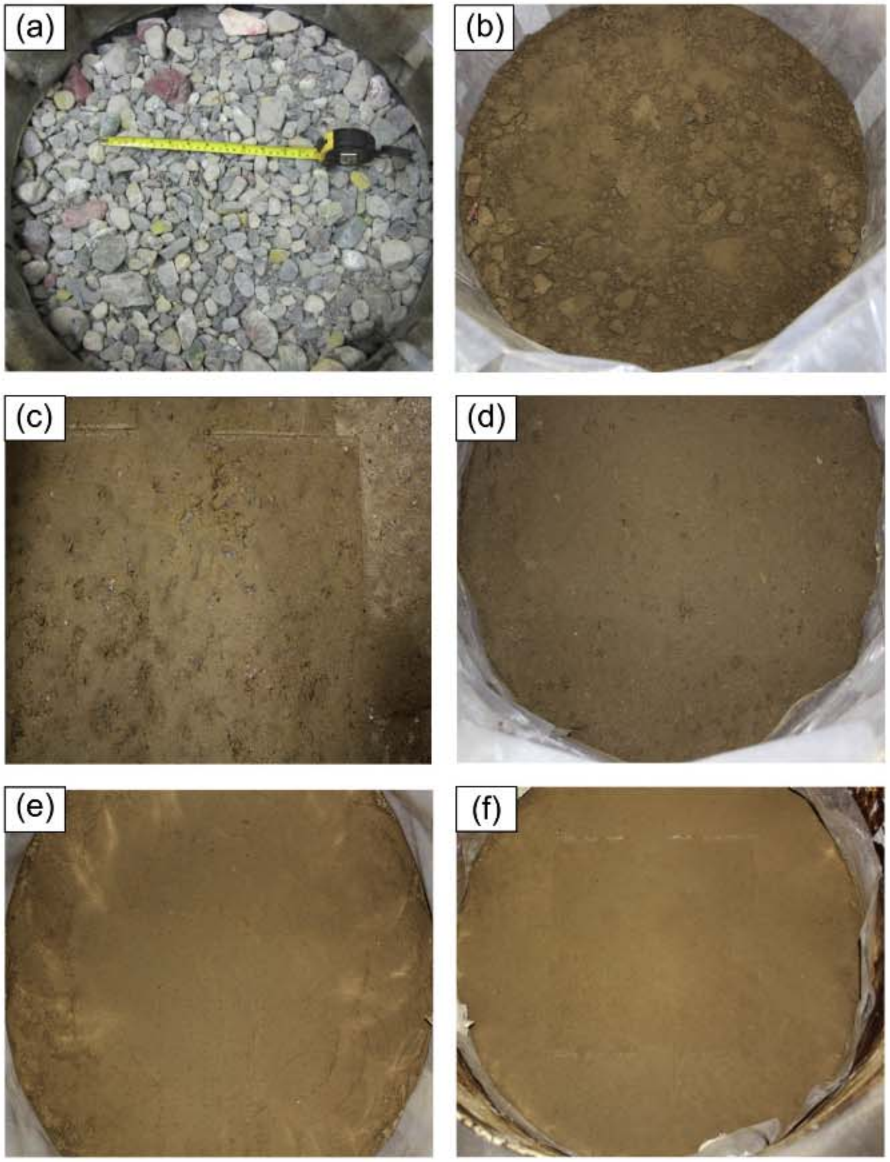

Fig. 4. Photograph of (a) underliner material UL1 as used in Test 1, (b) underliner material UL2 as used in Test 2, 2A, (c) underliner material UL3 as used in Test 3, 3A, (d) underliner material UL4 as used in Test 4, (e) underliner material UL5 as used in Test 5, 5A, 5B, 7, 7A, 8, 8A and (f) underliner material UL6 as used in Test 6.

of 12%. For Tests 9 and 9A, the clay was compacted at standard Proctor optimum water content of 12%. For Tests 10 and 10A, it was compacted at 16% (i.e., standard Proctor optimum plus 4%) with sufficient energy to achieve the same compacted dry density as in Test series 9 (i.e., the as-placed dry density was 1900 kg/m^3 for both Test series 9 and 10).

3.3. Test procedure

In each experiment, the underliner material (or foundation soil for the experiments with a GCL) was compacted in three 50-mm-thick lifts with a modified compaction procedure used to achieve the same compaction energy as used in the standard Proctor test but allowing for the larger size of the test apparatus compared to the standard Proctor mold. After compaction of the underliner (and placing of the GCL when a GCL was used), a 270-mm-square, 0.4-mm-thick, soft lead sheet was placed in the center of the cell to permanently preserve the deformation of the geomembrane after removal of the load. A smooth 1.5-mm-thick, 570-mm-diameter geomembrane was then placed on top of the underliner material and lead sheet. Except for Test 1A, no protection layer was placed above or below the geomembrane. In Test 1A, a nonwoven needle-punched geotextile with mass per unit area of 540 g/m^2 was placed directly above the geomembrane as a protection layer.

Table 4
GCL thickness before and after each test.

Test	Initial thickness (mm)			Final thickness (mm)		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum
7	8.7	7.1	10.3	5.3	2.9	7.7
7A	9.3	8.0	10.5	6.0	4.0	8.0
8	8.5	7.2	9.8	6.5	5.9	7.1
8A	7.9	6.8	9	5.8	5.1	6.5

Except for Test 2A, the geomembrane used was HDPE. In Test 2A, 1.5-mm-thick LLDPE was used to allow a comparison with the results from Test 2 with a 1.5-mm-thick HDPE geomembrane. Both geomembranes were manufactured by Solmax International Inc., Varennes, Quebec. The measured tensile stress–strain properties of the geomembranes are given in Table 5.

Table 5
Index stress–strain properties (measured in the machine direction) of the 1.5-mm-thick HDPE and LLDPE geomems studied (Tested following ASTM D6693 unless otherwise noted).

Property	HDPE		LLDPE[a]	
	Mean	Standard deviation	Mean	Standard deviation
Yield strength (kN/m)	27	1	22.4	0.5
Break strength (kN/m)	46	5	51.8	7.5
Yield strain (%)	24	2	23	0.5
Break strain (%)	830	80	880	104
Crystallinity (%)(ASTM E794)	48	–	38	–

[a] Abdelaal et al. (2012).

After placement of the geomembrane, the 300-mm-thick overliner material was placed on the geomembrane at a water content of 1.2%, without compaction, achieving a bulk density of approximately 1580 kg/m^3. The grain size distribution of overliner material (OL, Fig. 2) was based on the upper bound of the envelope given by Lupo and Morrison (2007). The overliner had $D_{85} = 30$ mm, $D_{60} = 19$ mm, $D_{30} = 10$ mm, $D_{10} = 2.5$ mm, a uniformity coefficient of 7.6, coefficient of gradation of 2.1, and an estimated hydraulic conductivity of 6×10^{-2} m/s.

A separator geotextile was placed above the overliner and then a 50 to 70-mm-thick layer of fine to medium sand was placed on the geotextile to protect the bladder from potential puncture by the overliner gravel. The sand was leveled, another geotextile placed over the sand, and a rubber bladder installed above the geotextile. The bladder was secured into place between the flanges of the test apparatus.

At the start of each test, water pressure was applied to the bladder in increments of 200 kPa every 10 min (to allow the system to respond to the pressure increment) until the target pressure of 2000 kPa was reached. The 2000 kPa pressure was applied for 100 h for Test series 1–6, 9 and 10. For Test series 7 and 8, the load was applied for 168 h to allow time for the GCL in Test series 7 to consolidate and the GCL in Test series 8 to hydrate from the subsoil under the applied load. The experiments were conducted at a temperature of 22 °C.

After the completion of a test, the test cell was depressurized and the materials removed to allow examination of the geomembrane. Each geomembrane sample was examined visually for scratches, signs of yielding, punctures, or notable indentations. Punctures were identified visually with the help of a back-light in a dark room.

The major indentations in the lead sheet at the end of a test were identified and the surface was scanned using a Laser scanner to quantify indentations and hence allow the evaluation of the strains using the method of Tognon et al. (2000).

4. Results

All experiments were conducted with the same overliner and at 2000 kPa so that the differences in results are predominantly due to the other factors varied (underliner, geomembrane, or protection layer) rather than the overliner. The effects of these variables will be discussed in the subsections below. Unless otherwise noted the results are for 1.5-mm HDPE geomembrane and no protection layer.

4.1. Response of geomembrane for underliners UL1 and UL2 (Tests 1, 1A, 2)

Underliner UL1 was the coarsest examined. In this case (Test 1) there were nine pin-hole sized punctures (Fig. 5a). All were from the bottom of the geomembrane and hence are attributed to the underliner. Six of nine punctures were on the sides of the indentations; the other three were at the tip. Eight of the nine punctures were outside the 270 mm square lead sheet (placed in the centre of cell) and hence the deformations and strain are not known at most of the puncture locations. Brachman et al. (2011) described these punctures as ductile tears. At the one location where a puncture was over the lead sheet, the indentation was 5.4 mm deep, 25 mm wide and the maximum strain was 33%. The lead sheet was not torn at this location. The eight largest indentations in the lead sheet were scanned. All large indentations were from the bottom and resulted from gravel in the underliner.

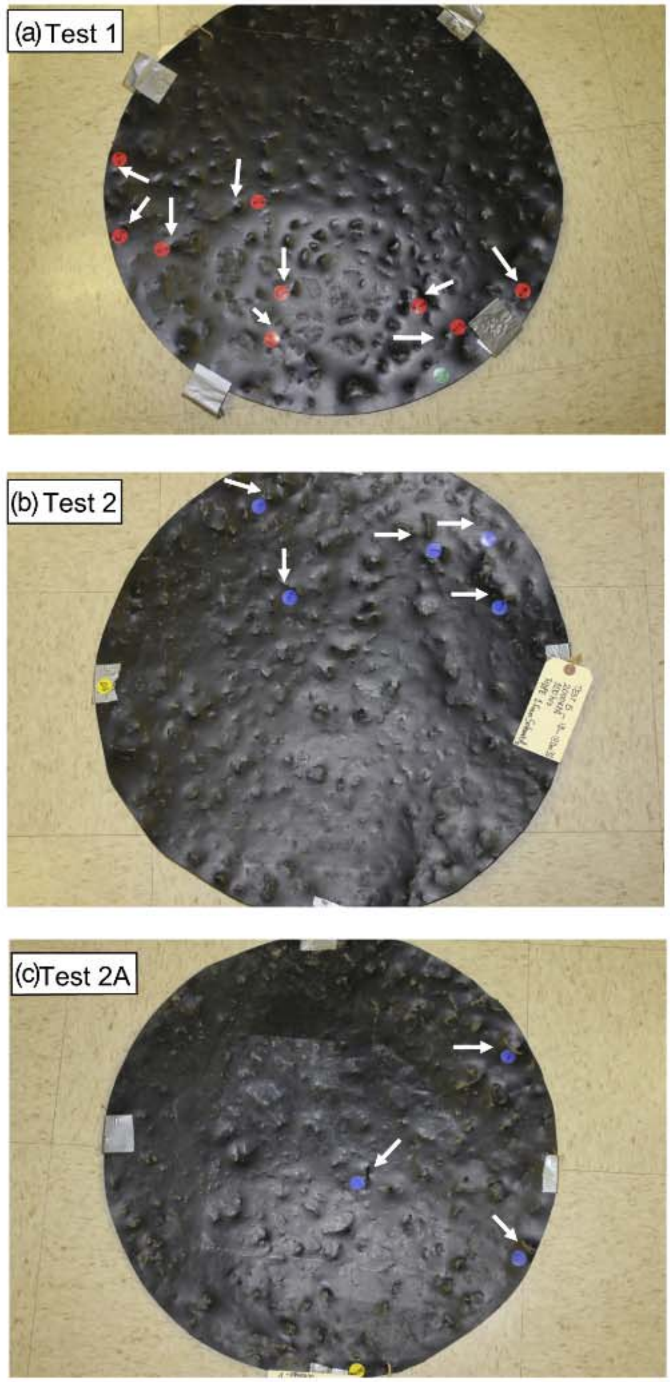

Fig. 5. Photographs of bottom of geomembrane after test with puncture locations shown by arrows for: (a) Test 1 (UL1), (b) Test 2 (UL2) HDPE geomembrane, and (c) Test 2A (UL2) LLDPE geomembrane.

The maximum indentation depth was 8.3 mm while the average depth of the eight largest indentations was 5.8 mm; thus at the location of the puncture, the depth of the indentations was less than the average of the eight most prominent indentations in the lead sheet. The maximum strain was 40% and for the eight indentations scanned (Fig. 6a) the average strain was 28%. Toward the centre of the lead sheet there were two indentations with strains (40% and 36%) larger than that at the puncture (33%) which coincided with the lead sheet and was located near the edge of the lead sheet. It is not known whether the fact that most punctures were outside the lead sheet is coincidence or observer effect (i.e., the use of the lead sheet to measure strains reduced the probability of a puncture where the lead sheet was present, possibly because it provided some protection to the geomembrane). However, it is known with certainty that there were: (a) many punctures, and (b) excessive strains at locations where there were no short-term punctures. Thus, this underliner was too aggressive for the geomembrane and hence unsuitable for these conditions.

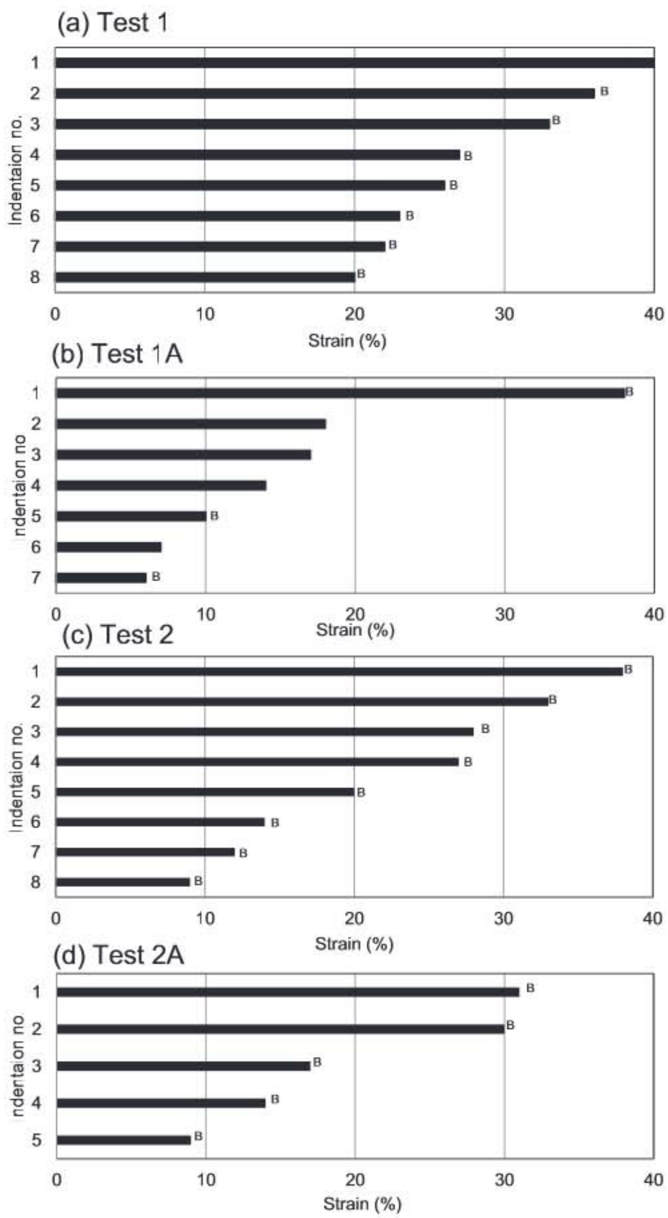

Fig. 6. Strains calculated for scanned indentation for: (a) Test 1 (UL1), (b) Test1A (UL1 modified and geotextile protection over geomembrane) (c) Test 2 (UL2, HDPE), and (d) Test 2A (UL2, LLDPE). Indentations were from the top (overliner) unless a "B" indicates it was from the bottom (underliner).

An experiment was conducted using the same underliner (UL1) and overliner but where silty sand was sprinkled on the top of underliner to fill in the upper voids and a 540 g/m^2 needle-punched nonwoven protection geotextile was placed on the top of the geomembrane. In this case (Test 1A) there were no punctures and the sand layer appears to have been effective to this extent. Since none of the punctures in Test 1 were from the overliner, the presence of the geotextile above the geomembrane is not considered to have affected puncturing. However despite the thin sand layer below and the geotextile protection layer above the geomembrane, there were still significant indentations and strains. The seven most prominent indentations (with strains $\geq$6%) were scanned. Of these, three were from the bottom and four from the top. The maximum indentation was 6 mm deep and the average depth was 4.3 mm. Thus, the indentations were a little less severe in this case than in Test 1; however the maximum strain was still large. The profile of the indentation giving the largest tensile strain (38%) is shown in Fig. 7a and the strains calculated from this profile using the Tognon et al. (2000) method are shown in Fig. 7b. The other six indentations scanned had lower strains (Fig. 6b) of 18% or less and were smaller than at any of the eight indentations scanned for Test 1 (minimum of 20%, Fig. 6a). This suggests that the surface treatment of the underliner did have a beneficial effect. However with three of the four largest strains (18%, 17% and 14%; Fig. 6b) being induced by indention from the overliner it is apparent that the 540 g/m^2 geotextile protection layer was not sufficient to prevent significant strains due to the overliner.

Test 2 examined UL2 (Fig. 2) which corresponded to the coarser bound of the cases examined by Lupo and Morrison (2007). For this case, there were five punctures (Fig. 5b) with one of them being above the lead sheet (near the edge). The strain of 34% for the puncture above the lead sheet was essentially identical to the 33% for Test 1 with UL1. All significant indentions in the lead sheet/geomembrane were from the underliner below. For the eight indentations considered worthy of scanning, the maximum depth was 8.0 mm. The strains at these indentations (Fig. 6c) ranged from

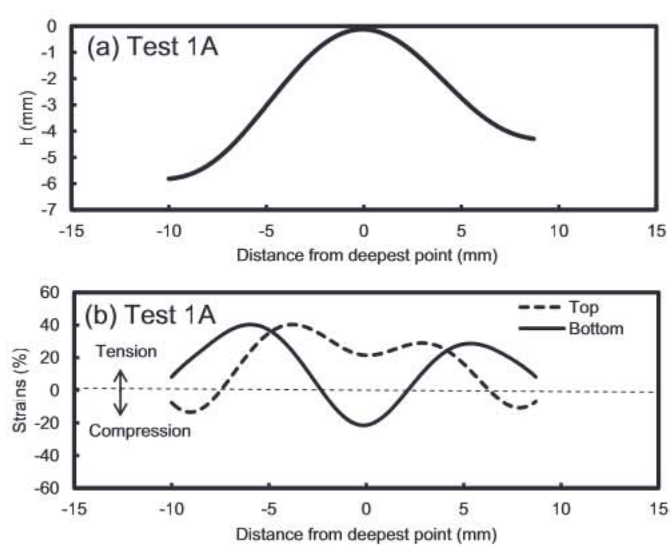

Fig. 7. The indentation from a gravel particle in the underliner giving the maximum strain for Test 1A: (a) Deformed shape, and (b) calculated strain. Geometry, *h* is the height of the indentation measured from the deepest or highest (in this case highest) point of the indentation. Tensile strains plotted as positive. Note that there is tension through the entire geomembrane thickness on both sides of the indentation.

a maximum of 38% (very close to the 40% for Test 1 and UL1) to a minimum of 9%, with five indentations having ≥20% strain (compared to eight for Test 1 and UL1). This while UL2 was a little less aggressive than UL1, this underliner was also too aggressive for the geomembrane and hence unsuitable.

4.2. Effect of maximum particle size and grading curve with 15% fines (UL2, UL3 and UL4)

Underliners UL2 and UL3 have the same maximum particle size (80 mm) and both have 15% fines but UL3 is very well graded (with very consistent slope index values of $s_{100-80} = 1.1$, $s_{80-60} = 1.5$, $s_{60-40} = 1.6$, $s_{40-20} = 1.5$) as compared to UL2 which exhibits a sharp change in slope at about D_{40} (slope index values of $s_{100-80} = 2.3$, $s_{80-60} = 2.2$, $s_{60-40} = 2.2$, $s_{40-20} = 0.7$; Table 3 and Fig. 2) and so a comparison of the results for Test 2 with those for Tests 3 and 3A allows an assessment of the effect of the grading of the underliners on geomembrane performance. The effect was significant. Whereas there were five punctures in Test 2 (UL2), there were no punctures in the duplicate Tests 3 and 3A (UL3). For Test 3 there were five indentations scanned. Peggs et al. (2005) suggested a maximum allowable strain in an HDPE geomembrane of 6% for good long-term geomembrane performance (although the validity on this number has yet to be verified). Taking this as a limit, two indentations were classified as significant (i.e., having a strain greater than 6%). These two were caused by gravel in the underliner and gave strains of 13% and 9% (Fig. 8a). The other three indentations scanned were from the overliner but the maximum strain for these indentions was 5%. In contrast, Test 2 (UL2) there were eight indentations (all from the underliner) with strains ≥9% (Fig. 6c).

Test 3A was a duplicate of Test 3 and was conducted to assess the variability in results and confirm that the much better performance observed for UL3 than UL2 was not an anomaly. The maximum depth of indentation was 3.2 mm for Test 3 and 5.7 mm for Test 3A, compared to 8.0 mm for Test 2. In neither Test 3 nor duplicate 3A was there any puncture (compared to five punctures in Test 2). To all practical purposes, the maximum strains (13% and 14%) in the duplicate experiments over UL3 (Fig. 8a) were identical and much less than the maximum strain of 38% in Test 2 (UL2). In Test 3, the two indentations with the largest strains were from the underliner with an average strain of 11%. For Test 3A the four indentations with the largest strains were from the underliner and had an average strain of 12.5% which was very close to the 11% for Test 3. Thus there appears to be very consistent results from these duplicate tests over UL3 which, when compared to Test 2 (UL2), suggest that the shape of the grading curve (Fig. 2) is much more significant, in terms of potential puncture and the magnitude of the strains, than the maximum particle size.

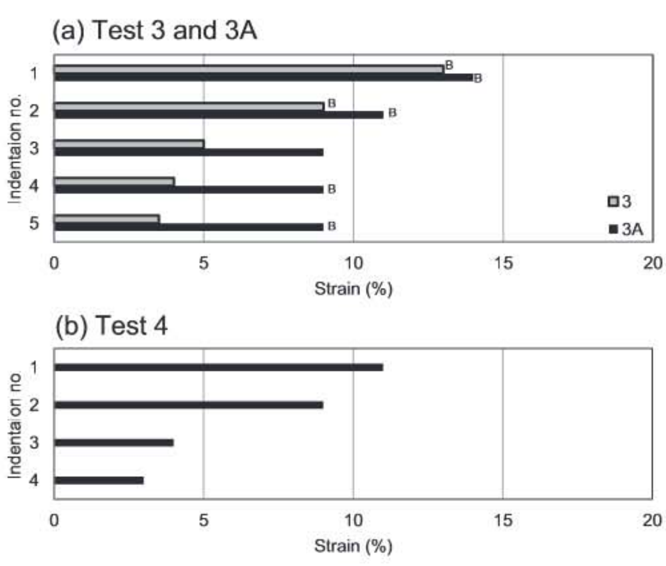

Fig. 8. Strains calculated for key indentations in (a) Tests 3, 3A for underliner UL3, and (b) Test 4 with underliner UL4. Indentations were from the top (overliner) unless a "B" indicates it was from the bottom (underliner).

To investigate the effect of the maximum particle size, two well graded underliners with 15% fines but very different maximum particle sizes (80 mm for UL3 and 10 mm for UL4) were examined. There were no punctures for either underliner (Tests 3, 3A or Test 4). The maximum depth of indentation in the lead sheet was 3.2 mm (Test 3) and 5.7 mm (Test 3A) over UL3 and 2.6 mm for UL4, however the source of the maximum indentations was different. Over UL3, two (Test 3) and four (Test 3A) of the significant indentations were from the underliner; over UL4 there were only two significant indentations (i.e., giving >6% strain) and they were from the overliner. The maximum strain in Test 4 (UL4) of 11% (Fig. 8b) was a little smaller than the maximum strains from the underliner for Test 3 and 3A (i.e., 13% and 14%) and a little larger than the maximum strains due to the overliner in Test 3 and 3A (i.e., 5% and 9% respectively).

Considering the underliners examined above (UL2, UL3 and UL4), it may be concluded that for a well graded material the maximum particle size (at least ranging from 10 mm to 80 mm as examined here) can affect the source and to a much lesser extent the magnitude of the strains in the geomembrane, but that the shape of grading curve has a much greater effect on the potential for puncture and the magnitude of the strains in the geomembrane than the maximum particle size.

4.3. Geomembrane performance over underliners UL5 and UL6 with 15% fines

The underliners considered above all had gravel, and in some cases cobbles. The underliners considered in this section were silty sand (UL5) and sandy silt (UL6) with no gravel in either case (Fig. 2). In both cases it was expected that the overliner would dominate in terms of being the source of indentations. These experiments, and those for GCLs and compacted clay discussed later, were to examine how the nature of the underliner affects the indentations and strains caused by a given overliner.

Triplicate experiments were conducted over UL5 (silty sand) to assess variability. The deepest indentations were 2.6 mm, 4.0 mm, and 3.6 mm and the maximum strains were 18%, 15% and 18% for Tests 5, 5A and 5B respectively (Fig. 9a). There were 4, 5 and 6 indentations with strains exceeding 6% with average strains of 14.3%, 11.0% and 13.7% for Tests 5, 5A and 5B respectively. Thus while there is some variability, the results are relatively consistent.

The maximum strains developed over UL5 (15–18%) exceed those obtained over UL3 (13–14%) or UL 4 (11%) suggesting that the absence of gravel in the underliner does not mean smaller strains in the geomembrane if the underliner is well graded.

Test 6 (over sandy silt UL6; the finer bound of the cases examined by Lupo and Morrison, 2007) gave a maximum indentation of 2.6 mm which was within the range observed for UL5. The maximum strain of 13% (Fig. 9b) was a little smaller than the maximum strains obtained over UL5 (15–18%; Fig. 9a). There were three indentations exceeding 6% strain with an average strain of 10.7% for these indentations (compared to 11.0–14.3% over UL5). The strains obtained with UL6 were similar to those obtained with UL3 and slightly greater than obtained for UL4 discussed above.

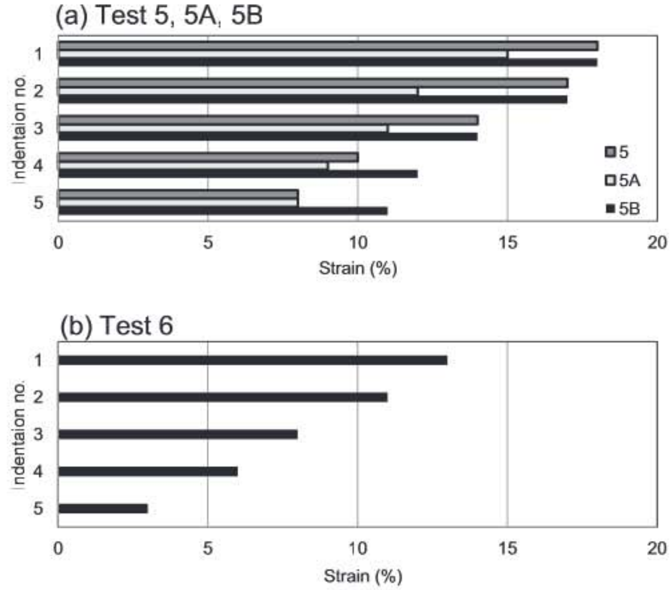

Fig. 9. Strains calculated for key indentations for (a) Tests 5, 5A, 5B with underliner UL5, and (b) Test 6 with underliner UL6. All indentations were from the top (overliner).

Of the granular underliners examined (UL1–UL6), the best performance was for the well graded gravelly sand with some silt (UL4) with all indentations being from the overliner (as they were for ULs 5 and 6 as well) but where it offered sufficient support to minimize the strains in the geomembrane due to the overliner. Nevertheless even in this case the maximum strain of 11% is almost double the maximum recommended by Peggs et al. (2005) for ensuring good long-term performance of the geomembrane.

4.4. Geomembrane performance with a GCL over sand (UL5) underliner

The first GCL case (Tests 7, 7A) involved a GCL underlain by silty sand (UL5) foundation layer where the GCL was hydrated to 86% moisture content at low stress (20 kPa) before application of the heap leach loading which resulted in final water contents of 66% and 62%. The partially prehydrated thickness just prior to the experiment (Table 3) was 8.7 ($\pm$1.6) mm and 9.3 ($\pm$1.6) for Tests 7 and 7A respectively. The loading reduced these GCL thicknesses to 5.3 ($\pm$2.4) mm and 6.0 ($\pm$2.0) mm. Part of this reduction (as represented by the changes in the average thickness) was due to consolidation under 2000 kPa average stress. However the increase in the variability of the thickness represents the effect of local indentations in the GCL due to gravel particles in the overliner. As a result, in this case the largest indentations were 5.1 mm and 8.0 mm deep and the maximum strains (Fig. 10a) were 14% and 21% for duplicate Tests 7 and 7A respectively. In both cases there were six indentations corresponding to strains exceeding 6% and the average strains for these indentations were 11.0% and 15% for Tests 7 and 7A respectively. The variability in these duplicate tests was much greater than that observed for any of the cases with a granular underliner alone.

In the second case (Tests 8, 8A), the GCL was hydrated from the foundation layer during the test, under a pressure of 2000 kPa, to a final water content of 55%. The off-the-roll thickness just prior to the experiment (Table 3) was 8.5 ($\pm$1.3) mm and 7.9 ($\pm$1.1) for Tests 8 and 8A respectively. The hydration under 2000 kPa load resulted in final GCL thicknesses of 6.5 ($\pm$0.6) mm and 5.8 ($\pm$0.7) mm. Thus hydration under greater stress (Test Series 8) appeared to give less

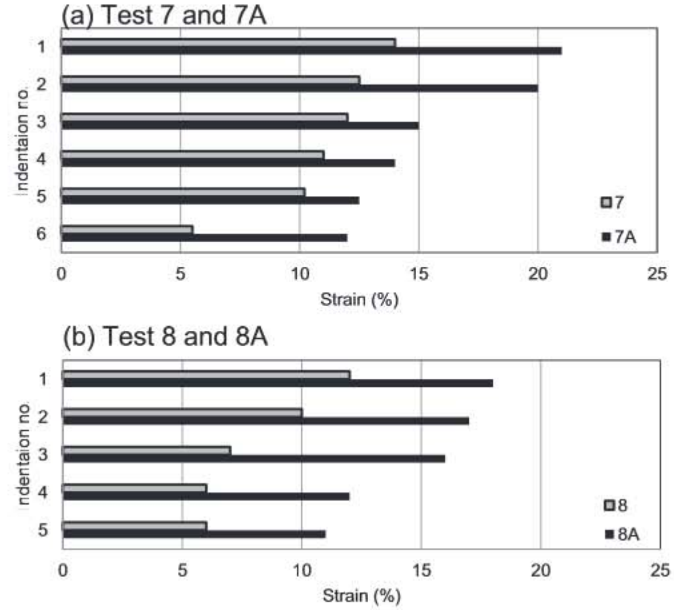

Fig. 10. Strains calculated for key indentations for (a) Tests 7, 7A with a prehydrated GCL, and (b) Tests 8 and 8A with GCLs hydrated from silty sand subgrade under 2000 kPa stress. All indentations were from the top (overliner).

variability in thickness than was obtained when the GCL had been partially prehydrated before significant load was applied (Test series 7).

For Test series 8, the deepest indentations were 3.3 mm and 5.2 mm and the maximum strains were 12% and 18% for Tests 8 and 8A respectively. There were three and five indentations with geomembrane strains in excess of 6% with average strains for these indentions of 9.7% and 14.8% for Tests 8 and 8A respectively. Thus again there was more variability between duplicate tests than was observed for granular underliners but slightly smaller strains when

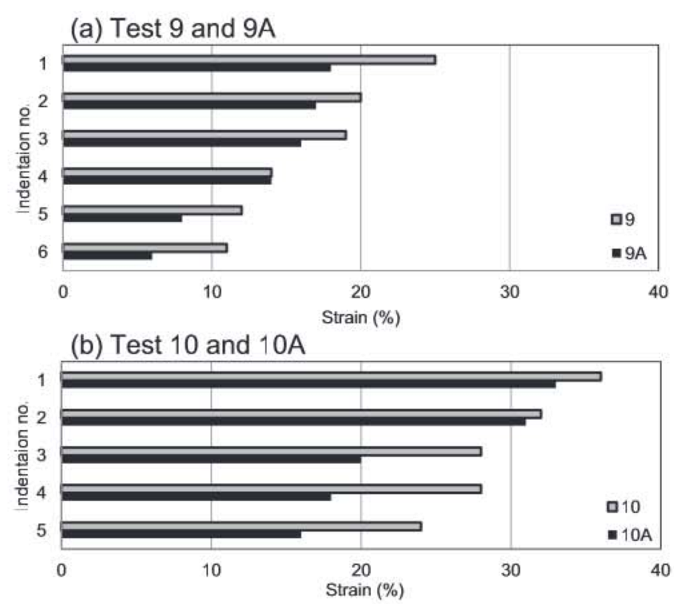

Fig. 11. Strains calculated for key indentations for (a) Tests 9, 9A with a clay liner compacted at standard Proctor optimum water content, and (b) Tests 10 and 10A with a clay liner compacted at water content of standard Proctor optimum plus 4%. All indentations were from the top (overliner).

the GCL was hydrated under load than when it was partially prehydrated before loading.

Test series 7 and 8 suggest that when on a relatively deformable (partially prehydrated) GCL, the indentations and strains are very sensitive to the arrangement of the particles in the overliner (much more so than when over a firmer foundation). As was the case with the granular underliners, the strains in the geomembrane may be too large for good long-term performance but there were no punctures for any of the experiments involving GCLs (or ULs 3–6) for the conditions examined.

4.5. Geomembrane performance with a compacted clay liner

The experiments on clay compacted at its optimum water content gave maximum indention depths of 5.4 mm and 6.0 mm and maximum strains of 25% and 18% for Tests 9 and 9A respectively (Fig. 11). There were 7 significant indentations (i.e., strains exceeding 6%) in Test 9 with an average strain of 15.9% while in Test 9A there were 5 significant indentations with an average strain of 14.6%.

When the clay was compacted at a water content of optimum plus 4%, the maximum indentation depths increased to 8.5 mm and 7.0 mm while the maximum strains increased to 36% and 33% for Tests 10 and 10A respectively. Again there were 7 and 5 significant indentations but this time with average strains of 25.3% and 23.6% for Tests 10 and 10A respectively (Fig. 11). These are very large strains although there were no punctures (either above or outside the lead sheet) for any compacted clay case examined.

The strains in the geomembrane obtained when the liner was compacted 4% wet of optimum were considerably greater than those when it was compacted at optimum, indicating again, that the more deformable the foundation the greater the strains induced in the geomembrane from a given (coarse) overliner.

4.6. HDPE versus LLDPE (Tests 2 and 2A)

To assess the effect of HDPE versus LLDPE, 1.5-mm-thick geomembranes of HDPE and LLDPE (Table 4) were used over underliner UL2, all other things being the same. The LLDPE was from the upper end of the LLDPE range of densities (to give better chemical resistance). The results for Test 2 using HDPE were discussed above and here only comparative numbers are given with respect to Test 2A with the LLDPE. In both cases there were punctures (five in Test 2 and three in Test 2A; Fig. 5b and c) with one puncture above the lead sheet in each case. For the HDPE, the puncture occurred at a location with a maximum strain of 34% and in the LLDPE it corresponded to an indentation with a maximum strain of 17% (at a location relatively close to the middle of the lead sheet; Fig. 5c). As might be expected from two tests with a similar underliner and overliner, the indentation geometries observed for HDPE and LLDPE were similar. The maximum depth of the indentations were 8.0 mm and 7.6 mm for Test 2 and 2A respectively and in both cases all major indentations were from gravel in the underliner. The maximum strains were 38% and 31% (Fig. 6c and d) although for Test 2A with the LLDPE there were only two strains greater than 20% (compared to five for Test 2) but, as noted above, there was a puncture at a strain of 17% with the LLDPE. The difference in strains between the two tests is attributed to the variability associated with using coarse gravel in two tests where the strains will be highly dependent on the location and orientation of individual gravel particles rather than the effect of the choice of geomembrane. Thus, at least for this LLDPE, there was no apparent improvement in performance for the LLDPE versus the HDPE over the same underliner (UL2). The effect the difference between LLDPE and HDPE under long term stress still requires examination.

5. Conclusions

A review of 92 heap leach projects from 15 countries indicated that:

- In approximately 51% of cases, the ore heights were 50 m or less (i.e., ≤1000 kPa of applied pressure) although these were mostly either older cases or dynamic heaps. In 90% of cases the heaps were 100 m or less (≤2000 kPa), but in 10% of cases the ore height exceeded 100 m with a maximum of 238 m (≤4800 kPa).
- The underliner contained considerable fines (possibly clay) in 48%, native soil in 9%, a GCL in 5%, tailings in 4%, and silt/sand in 3% of cases; the underliner details were not given in 30% of cases.
- HDPE was used in 75% of cases, LLDPE in 22% of cases, and PVC in only 3% of cases; although LLDPE was being considered in about 50% of cases currently in the design phase.
- 1.5-mm-thick geomembrane was the most common, being used in 46% of cases (40% HDPE, 6% LLDPE).
- 2-mm-thick geomembrane was used in 45% of cases (31% HDPE, 14% LLDPE).
- 2.5-mm-thick geomembrane was only used in 5% of cases.
- The overliner had a nominal size of 12 mm in 20%, 19 mm in 53%, 25 mm in 13%, and 38 mm in 13% of cases where it was reported.

Experiments were conducted in a cylindrical steel pressure vessel with an inside diameter of 590 mm and height of 500 mm. All experiments were conducted with the same (gravel, some sand) overliner at 22 °C and 2000 kPa. Attention was focused on the effect of different underliners on puncturing and geomembrane strains in a 1.5 mm HDPE geomembrane, although the effects of a protection layer and a 1.5 mm LLDPE geomembrane were also examined. For the conditions examined, the following conclusions were reached:

- When the geomembrane was over an underliner of gravel with some sand or a gravel and sand, there were a significant number of punctures and maximum tensile strains of 38–40% in the geomembrane. Thus, these underliners were not suitable for the conditions examined.
- When the underliner was a well graded sand and gravel with some silt, there were no punctures; however the maximum geomembrane tensile strain from the underliner was 13% and 14% in the duplicate experiments. This underliner had the same 80 mm maximum particle size and 15% fines as a gravel and sand underliner which exhibited a sharp change in the grading curve at about D_{40} for which there were five punctures and a maximum strain of 38%, demonstrating the critical role of the underliner grading curve.
- Experiments conducted with two well graded underliners with 15% fines but very different maximum particle sizes of 80 mm and 10 mm gave maximum tensile strains of 13–14% (for the sand and gravel with some silt) and 11% (gravely sand, some silt); however in the former case the maximum strain was due to an indentation from the underliner while in the second case the maximum strain was due to an indentation from the overliner.
- The shape of underliner grading curve had a much greater effect on the potential for puncture and the magnitude of tensile strains in the geomembrane than the maximum particle size.
- For silty sand and sandy silt underliners (with no gravel in either case) the maximum geomembrane tensile strains were 15–18% and 13% respectively and all these strains were due to gravel in the overliner.

- Of the granular underliners examined, the best performance was for the well graded gravelly sand with some silt which offered sufficient support to minimize the strains in the geomembrane due to the overliner while not inducing any significant strains directly from the underliner. Nevertheless even in this case the maximum tensile strain of 11% was almost double the maximum recommended by Peggs et al. (2005) for ensuring good long-term performance of the geomembrane.
- For a GCL partially hydrated before application of the heap leach loading, the maximum tensile strains were 14% and 21% for duplicate tests. The magnitude of strains and variability was slightly reduced when the GCL was hydrated from the foundation layer under 2000 kPa pressure during the test, with the maximum tensile strains in duplicate test being 12% and 18%. In both cases there was more variability between duplicate tests than was observed for granular underliners, indicating a greater sensitivity to the arrangement of the particles in the overliner when the GCL was below the geomembrane than when there was just a granular underliner below the geomembrane.
- Duplicate tests of geomembranes on clay compacted at optimum water content gave maximum tensile strains of 25% and 18% compared to maximum tensile strains of 36% and 33% for duplicate tests with a geomembrane over clay compacted at a water content 4% wet of optimum (i.e., at the plastic limit). These are very large strains although there were no punctures for the compacted clay cases examined.
- The more deformable the foundation, the larger are the indentations and strains induced by a given overliner. Thus the short- and long-term performance of a geomembrane will not only depend on the grain size distribution and the size of particles in the underliner, but also on the deformability of the underliner and the interaction between the overliner particle size distribution with that deformability. This and the fact that there were geomembrane strains well in excess of 6% in all cases examined, suggests the need for a future study of the effects of different overliner grainsize distributions on the strains developed in geomembranes.
- Experiments conducted with a 1.5-mm-thick HDPE and 1.5-mm-thick LLDPE geomembrane over a gravel and sand underliner, indicated very similar behavior with puncturing of the geomembrane and maximum strains exceeding 30% on both cases. Thus, at least for the conditions examined, there was no apparent improvement in performance for the LLDPE versus the HDPE.
- A 540 g/m^2 geotextile protection layer above the geomembrane was not sufficient to prevent significant tensile strains (18%, 17% and 14%) in the geomembrane due to the overliner.

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