Comparison of interface shear strength characteristics of HDPE and LLDPE geomembrane interfaces

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ABSTRACT: A comparison study of interface shear strength parameters of textured high density polyethylene (HDPE) geomembranes and linear low density polyethylene (LLDPE) geomembranes sheared against two geotextiles and one geosynthetic clay liner commonly used in South African landfill lining systems is presented. Tests were performed using the 305 x 305 mm large direct shear box over a range of normal pressures of 25, 50, 100, 150, 200 and 300 kPa. A shear rate of 0.1 mm/min was used for geomembrane-GCL interfaces and a rate of 1 mm/min for geomembrane-geotextile interfaces.

It was found that LLDPE and HDPE geomembranes produced different friction characteristics when sheared against different geosynthetics. LLDPE geomembrane/ geotextile interfaces showed that the conventional linear failure envelopes did not always give the best regression relationship between shear stress and normal stress parameters for sheared interfaces. These geomembrane shear strength envelopes could be described more accurately as bilinear failure envelopes.

When a linear failure envelope was considered, at normal stresses less than 150kPa, LLDPE geomembrane peak interface shear stresses were higher than HDPE geomembrane peak shear stresses. Normal stresses greater than 150kPa indicated that HDPE geomembranes had higher peak interface shear stresses when compared to those produced by LLDPE geomembranes. From these observations, applications where low normal stresses (<150kPa) would be applied, such as in landfill capping systems, it was proposed to select LLDPE geomembranes and to use HDPE geomembranes where large normal stresses would be experienced, such as along the base and slopes of a landfill.

Keywords: Geomembranes, shear strength, landfills, friction angle

1 INTRODUCTION

Waste landfills in South Africa use protective liner systems that usually consists of several layers of geosynthetic materials and compacted clay. These liners act as hydraulic barriers and prevent toxic liquids generated by waste from leaking into surrounding ground water. Due to this function, the use of geosynthetics has been seen as an important environmentally friendly technique that has to be incorporated in the design of landfills (Shukla & Yin, 2006).

The type of geosynthetics used in a landfill differs from country to country. In South Africa, geosynthetic combinations used in landfill designs depend on the level of risk the disposed waste contains. The varying landfill containment barrier designs are separated into Classes A, B, C and D as shown in Figure 1 (The Government Gazette No 36784, 2013).

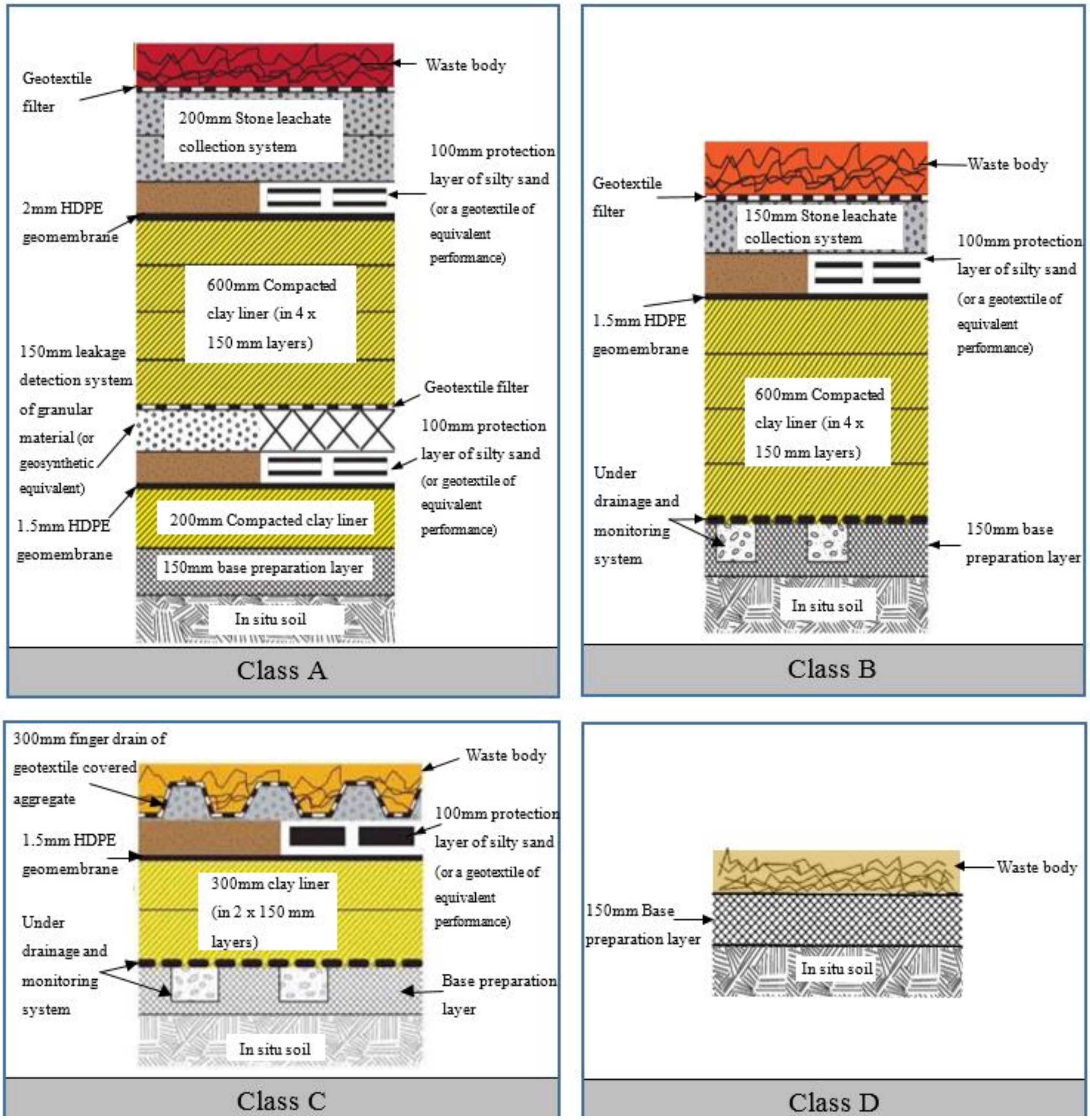

Figure 1: Landfill lining systems for Class A, Class B, Class C and Class D (The Government Gazette No 36784, 2013)

The liners described are excellent at cutting off the migration path of contaminants but the liners have certain mechanical behaviour limitations. For example, if these surfaces provide insufficient friction, these materials can result in geosynthetic interface frictional failure. The bond between the geosynthetic with soil and/or another geosynthetic depends on the interaction of their contact surfaces. Shear strengths of geosynthetic interfaces are needed for stability analysis in the design of a landfill base, slopes and a capping system required after the termination of landfill operations. It is therefore important that strict environmental laws control landfills and good structural monitoring practices are enforced. The environmental laws regulate shear strength characteristics by ensuring that testing of geosynthetics used in landfills is mandatory (Department of water affairs and forestry, 1998). Such regulation is important for critical interfaces to avoid slope stability related problems.

From Figures 1, the most common interface combinations found in landfills are geomembrane-soil, geomembrane-geotextile, geomembrane-Geosynthetic Clay Liners (GCL) and GCL-soil. Since geomembranes are the most common geosynthetic found in a modern landfill design, this research focussed solely on the geomembrane against other geosynthetic interfaces found in landfill lining systems. Geomembranes provide added assurance by preventing toxic liquids from migrating into the environment unlike compacted clay liners that only minimise possible migration (Koerner, 2005). As a result, the interface frictional strength of any geomembrane interface has to be determined with utmost care.

Geomembrane/geosynthetic interfaces had previously been studied by numerous authors (Bhatia & Kasturi, 1995; Russell, 1998; Fox & Kim, 2008; Bacas, 2015). Significantly more research has been done on HDPE geomembranes when compared to LLDPE geomembranes. And only a few had investigated whether a difference exists in interface friction values between Linear Low Density Polyethylene (LLDPE) and High Density Polyethylene (HDPE) textured geomembranes.

The ASTM D5321 and ASTM D6243 was used to conduct the laboratory investigations. A 305 x 305 mm large direct shear box on six different interfaces using five various geosynthetic materials was used to determine interface shear behaviour. By comparing the friction parameters obtained from HDPE and LLDPE tests, some clarification about the competence of one geomembrane over the other was observed.

2 EXPERIMENTAL WORK

2.1 *Materials*

The following section describes materials investigated in the laboratory test programme:

2.1.1 *Geomembranes*

Two textured polyethylene geomembranes (GM) were used during testing; one High Density Polyethylene (HDPE) and one Low Linear Density Polyethylene (LLDPE). Both geomembranes were co-extruded, double-sided textured geomembrane, with an asperity height of 0.4mm on each side and a nominal thickness of 1.5mm (GSE Environmental, 2015). These geomembranes were chosen because they are the most currently used in South African landfills and also due to the similarities in their properties which ultimately eliminates several variables.

2.1.2 *Geosynthetic Clay Liners (GCL)*

A GCL with a hydraulic conductivity of 2.56 x 10^{-11} m/s was selected for investigation. This GCL was chosen because of its frequent use in landfills where waste with low risk levels is disposed (i.e. Class C and Class D). The GCL had a woven polypropylene carrier geotextile and a nonwoven polypropylene cover geotextile sandwiching a layer of sodium bentonite through needle-punching. The needle-punched fibres were modified using a proprietary heat treating process thus permanently locking the fibres into place (Kaytech, 2016).

2.1.3 *Geotextiles*

The experimental program was conducted using two geotextiles commonly used in South Africa for a variety of functions; filtration, drainage, reinforcement and separation. One geotextile (GTA) was a nonwoven, polyester staple fibre needle punched geotextile with a thickness of 7.5mm under 2 kPa. This geotextile had a permeability of 2.6 x 10^{-3} m/s at 50mm head. The second geotextile (GTB) was a nonwoven needle punched continuous filament polyester geotextile. It had a thickness of 4.4mm under 2kPa, permeability 4 x 10^{-3} m/s at 50mm head and was selected because of its suitability to protect the geomembrane prior to the placement of the aggregate layer used for leachate collection.

2.2 *Test apparatus*

The equipment used for all tests was an automated 305 x 305 mm large direct shear box (Figure 2). The shear box was divided into two parts; the moving lower box and a static upper box. The shear box was able to allow a constant contact area between the geosynthetics being sheared.

A horizontal force was applied to allow constant horizontal displacement of the bottom box. A vertical load applied a normal stress on the top box cover that rested on the geosynthetics after the two boxes were set in place. In addition, a metal spacer with dimensions of 305 x 460 x 100mm was used because a soil sample was not required in the bottom box and a computer was used to attain the data. The following gripping systems were used for the different types of geosynthetics:

a) Clamping plates and bolts were located at the ends of both boxes. They allowed geosynthetics to be fastened to either the top or bottom box,
b) Textured plate designed to provide high friction which secured the test specimen to the shearing blocks. GCL interface shear testing required the gripping plate to minimise slippage and sliding while allowing the flow of water into and out of the test specimen.

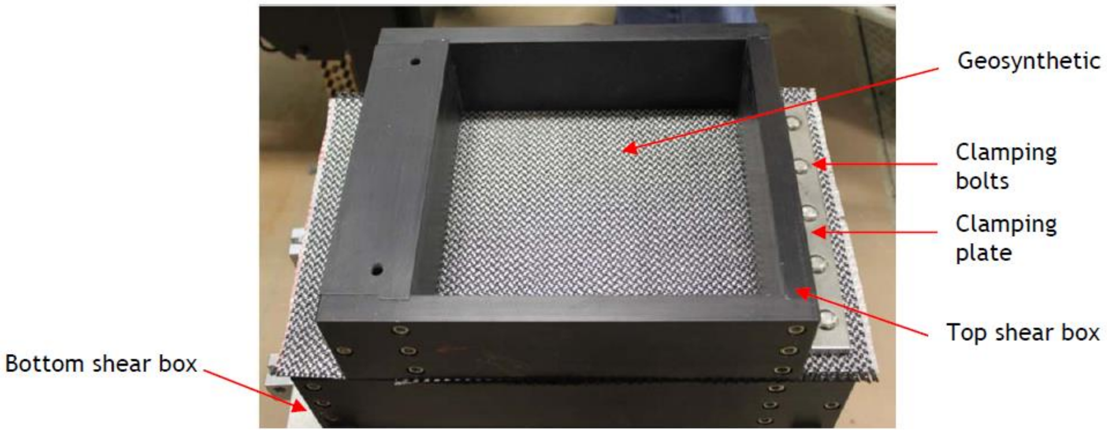

Figure 2: Large direct shear box set up with clamping plate and geosynthetic sample (Geocomp corporation, 2012)

2.3 *Test procedure*

The samples were cut using a mechanical saw. The size in which the geosynthetic samples were cut depended on which box the sample would be fixed onto. Samples fixed on the upper box were cut to be 305 x 325 mm and those on the lower box were cut to be dimensions of 305 x 500 mm. Once samples were cut into the required sizes, 10mm diameter gripping holes were punched into the geosynthytic. The holes allowed the sample to be fixed into place by the clamping device.

Some test samples required further preparation, such as Geosynthetic Clay Liners (GCLs). GCL samples needed to be hydrated and consolidated to match expected field hydration when it rains and while experiencing loading conditions from waste. Thus the GCLs were hydrated according to the ASTM D6243, before shearing took place.

Several authors recommended to have geosynthetic interfaces sheared at a shearing displacement rate of 1 mm/min and GCL interfaces to be sheared at a lower rate of 0.1 mm/min to minimise bentonite extrusion (Zornberg, 2005; Fox & Stark, 2015; Triplett & Fox, 2001; Fox & Kim, 2008). These shear rates were subsequently chosen to be used for the respective geosynthetics combinations in this research. The constant horizontal shear displacement rate was applied while a constant normal load was applied. These tests were run at six different normal loads, ranging from 25-300kPa. This range of normal stresses chosen assisted in identifying when the failure plane of a geosynthetic changed from a linear relationship to a bilinear relationship.

At the end of the test, the relative displacement of the bottom metal frame and geosynthetic, and the applied load were monitored using the computer and a respective interface relationships were plotted.

3 RESULTS, ANALYSIS AND DISCUSSION

3.1 *Investigation of direct shear test results*

The shear stress versus horizontal displacement relationships of all materials tested according to the direct shear test program are shown in Figure 3. For each type of geomembrane interface interaction, a separate graph was produced, Figure 3(a) to Figure 3(f). In each diagram, there are three sets of responses representing geomembrane-GTA, geomembrane-GTB and geomembrane-GCL interface tests, as indicated in the title at the top of the figures. There are six curves in each graph because each of the interface tests were conducted at six different normal pressures namely at 25, 50, 100, 150, 200 and 300 kN/m^2. The geomembrane/geotextile interfaces were tested dry and the geomembrane/GCL interfaces were tested under wet conditions. The maximum horizontal displacement for all tests conducted was 70 mm. After each test, no slippage or movement of the geosynthetic layers was observed at the clamps.

3.1.1 *Geomembrane and GTA*

The behaviour of a geomembrane/GTA interface is illustrated in Figures 3(a) and 3(b) which show that shear stress increased as the normal pressure increased. This was expected since the higher the applied normal pressure, the higher the induced contact stresses between the geosynthetic interfaces will be. This causes the contact surfaces to adhere and interlock more tightly thereby developing an increase in resisting interface shear stresses. Comparing the magnitudes of peak shear stresses, it can be noted that the LLDPE geomembrane had higher shear stress development at normal pressures lower than 150kPa and HDPE geomembrane had higher shear stress development at normal pressures greater than 150kPa.

The relationship between maximum shear stress and the applied normal pressure for geomembrane versus GTA is illustrated in Figures 4(a) and (b). Figure 4(a) to (f) shows the typical linear and possible bilinear Coulomb envelopes obtained from the data generated from the graphs in Figures 3(a) to (b). In each direct shear test, the maximum shear stresses were read-off from the graphs, plotted against respective normal pressures and had the best straight lines fitted. The summary of results obtained from Figures 3(a) to (f) are quantitatively given in Table 1. Where C_p is the intercept on the vertical (shear stress) axis which gives cohesion at peak, C_d is the cohesion when there is a dual relationship, ϕ_p for the linear best fit line inclination to the horizontal axis gives the peak internal friction angle of shearing resistance of the geosynthetics and ϕ_{d1} and ϕ_{d2} for angles formed by failure envelopes with a bilinear relationship. A bilinear relationship was observed for only LLDPE geomembranes.

The friction angles of LLDPE and HDPE geomembranes interfaces against GTA are indicated in Table 1. The HDPE geomembrane interfaces had the highest friction angles, $\phi_{p,}$ when compared to LLDPE parameters.

3.1.2 *Geomembrane and GTB*

The shear stress and horizontal displacement relationship of geomembrane versus GTB interface tests are shown in Figure 3(c) and (d). It was observed that, the HDPE GM shear stresses had a well-defined initial increase and then the interface shear stress decreased to a residual value with increasing horizontal displacement a phenomenon also known as strain softening. The shear stress vs horizontal displacement curves of the LLDPE GM versus GTB interfaces did not have well-defined strain softening behaviour. At low normal pressures, strain softening behaviour can be observed. Once higher normal pressures are reached, the curves showed a residual value with increasing horizontal displacement without a defined peak stress. Thus the HDPE and LLDPE GM interfaces did not have similar curves when sheared against the same geotextile (GTB). For HDPE geomembranes the peak shear stress was observed at horizontal displacements less than 30mm and less than 45mm in LLDPE geomembranes. Post peak stresses were measured around 50-60 mm for HDPE GM and 60-70mm for LLDPE GM.

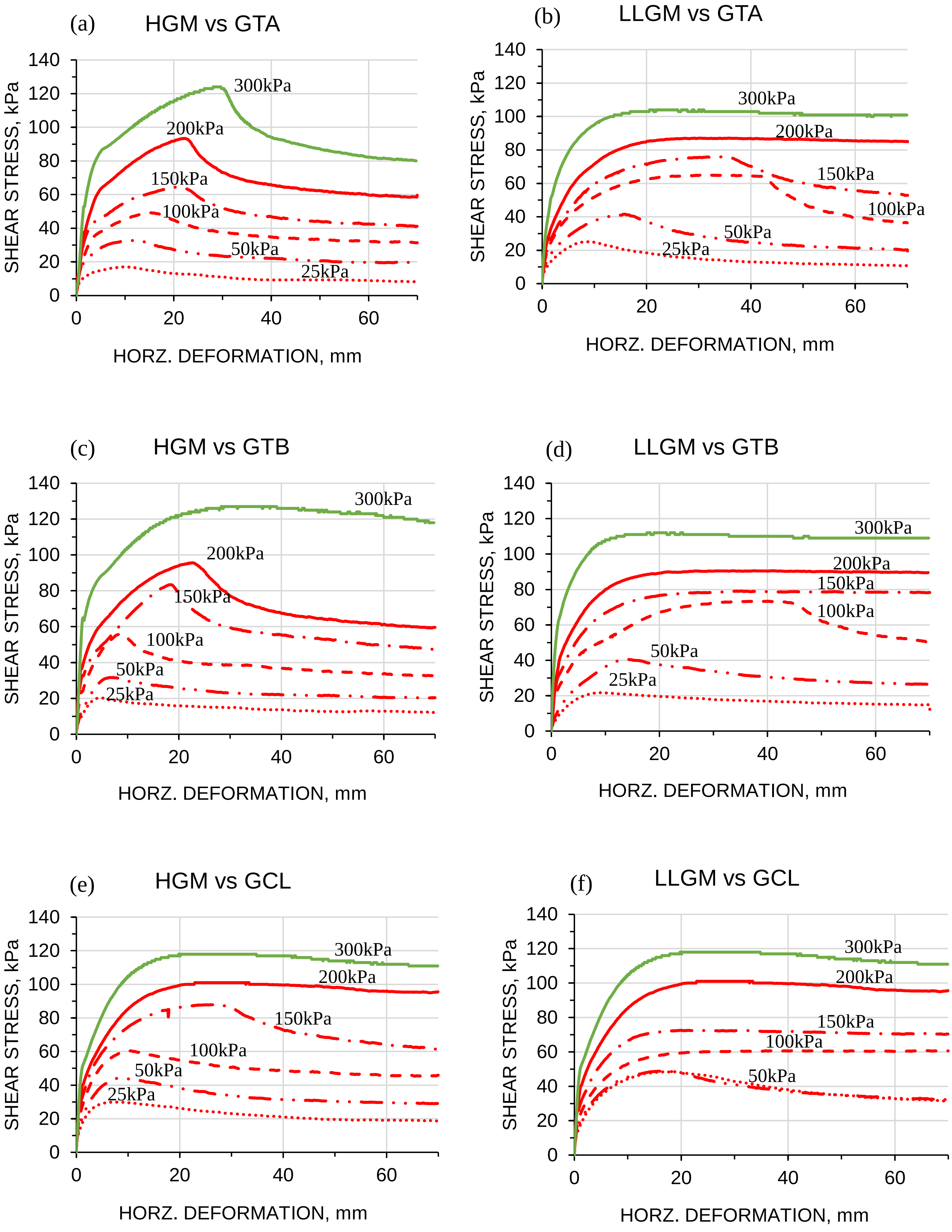

Figure 3: Shear stress versus horizontal displacement graphs from different interfaces

Table 1. Summary of direct shear peak cohesion and friction angle results

Geomembrane	Geosynthetic	Cohesion (kN/m^2)	Friction Angle (degrees)

		C_p	C_d	ϕ_p	ϕ_{d1}	ϕ_{d2}
HDPE	GTA	10.4	10.4	21.1		
	GTB	15.0	15.0	21.4		
	GCL	28.6	28.6	18.1		
LLDPE	GTA	28.8	28.8	15.4	45.2	21.1
	GTB	27.2	8.3	17.2	51.6	20.3
	GCL	37.2	19.6	15.4	45.3	23.1

Comparing the geomembrane/GTA with geomembrane/GTB interface shear stress versus horizontal displacement relationship results, an increase in shear stress at failure of GTB geomembranes was observed. The difference becomes more significant with increasing confining pressure. The shear resistance between the geomembrane and the GTA geotextile fabric is lower because, according to the data obtained from the direct shear tests, it seems apparent that the inclusion of a stiff geotextile on a geomembrane reduces the maximum shear stress achieved at failure.

Table 1 shows a comparison between the geomembrane/GTB and geomembrane/GTA interface friction angles. HDPE geomembranes have higher interface friction angles when sheared with GTA and GTB geotextiles compared to LLDPE geomembranes. The geomembrane/GTB interface friction angles of HDPE and LLDPE geomembranes were 21.4 and 17.2, respectively. It is evident that the geomembrane/GTB interface friction angles for the different geomembranes were not similar. This suggested that formulation of geomembranes may have an effect on the friction characteristics at the geomembrane/GTB interface.

In Figures 4(c) and (d), the failure envelopes of geomembrane/GTB interface in terms of interface strength parameters are shown. The results show a linear and bilinear shear strength versus normal stress relationship. HDPE geomembrane/GTB interface showed similar linear failure envelopes as HDPE geomembrane/GTA interface tests. Both these configurations had their LLDPE geomembrane interfaces form a bilinear failure envelope from 100kPa.

For both geomembrane/GTA and geomembrane/GTB interfaces, each straight best fit failure envelope shows that at normal stresses lower than 150kPa, LLGM had higher interface friction values. Normal stresses higher than 150kPa showed that HDPE geomembrane had higher friction parameters. These results can be interpreted to mean, the less stiff LLDPE geomembranes will be well suited for applications where low normal stresses will be experienced such as in landfill covers. While HDPE geomembranes are more appropriate where high normal stresses will be exerted such as along the base and slopes of landfills. If greater flexibility along the base and slope of a landfill than HDPE is required, then LLDPE geomembranes can be used. These findings supported results found by several authors indicating that the more flexible the geomembrane, the higher the friction angle (Bhatia & Kasturi, 1995; Vaid & Rinne, 1995; Koerner, 2005; Shukla & Yin, 2006).

3.1.3 *Geomembrane and GCL*

In Figure 3(e) and (f), a low degree of strain softening can be observed between geomembrane/GCL relationships when compared to that seen in geomembrane/geotextile interfaces. Both HDPE and LLDPE geomembrane shear stress vs horizontal displacement curves show similar behaviour at the different normal stresses tested. Defined peak stresses can be seen at lower normal stresses. At higher normal stresses, residual stress is achieved with increasing horizontal displacement and no defined peak stresses can be observed. During the shear test, the geomembrane experienced tension near the clamping area (Figure 2). Extension of the geomembrane occurred (Figure 5) which resulted in exceeded peak strength and which induced elongation of the geomembrane sample, resulting in shear strength curve illustrated in Figure 3(e) and (f) at 200 and 300kPa stresses for both HDPE and LLDPE geomembranes. This means the measured shear stress vs horizontal displacement is not the true material interface friction behaviour. As a result, this behaviour produced an irregular failure envelope.

(a)
LLDPE HDPE

(b)
LLDPE HDPE

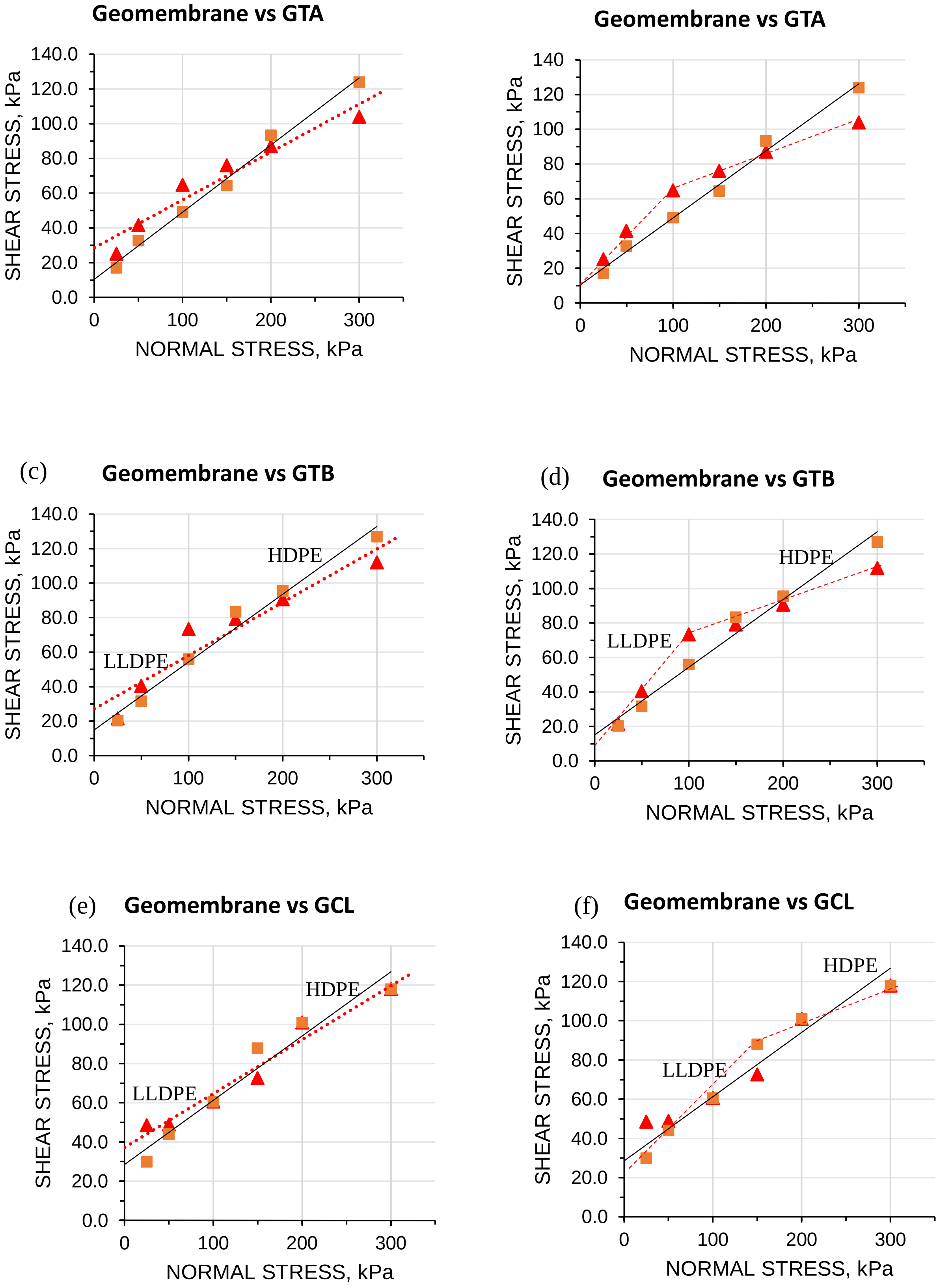

Figure 4: Linear and bilinear Mohr-Coulomb failure envelopes for LLDPE and HDPE geomembranes

The shear stress versus normal pressure behaviour of a geomembrane /GCL interface is illustrated in Figure 4(e) and (f). It is evident that at confining pressures lower than 150kPa, the maximum shear stresses obtained at both HDPE and LLDPE geomembrane/GCL interfaces, was higher than that at any geomembrane/geotextile interface. Straight line approximations of the failure envelope in Figure 4 showed that for geomembrane/geotextile interfaces, HDPE GM are well suited by a linear failure envelope while for a LLDPE GM a bilinear failure envelope is recommended. For geomembrane/GCL interfaces, HDPE GM have a bilinear failure plane while LLGM have a linear failure envelope. It is possible that this behaviour may be influenced by the geotextiles used in making the GCL cover layers. From Table 1, the friction angles for HDPE and LLDPE GM against a GCL were 18.1 and 15.4 respectively. Comparison of the investigated results show that the geomembrane/GCL friction angles were lower than any of the researched geomembrane/geotextile interface angles. It was noted that LLDPE GM interfaces had friction angles, ϕ_p similar to HDPE GM bilinear friction angles, ϕ_{d2}.

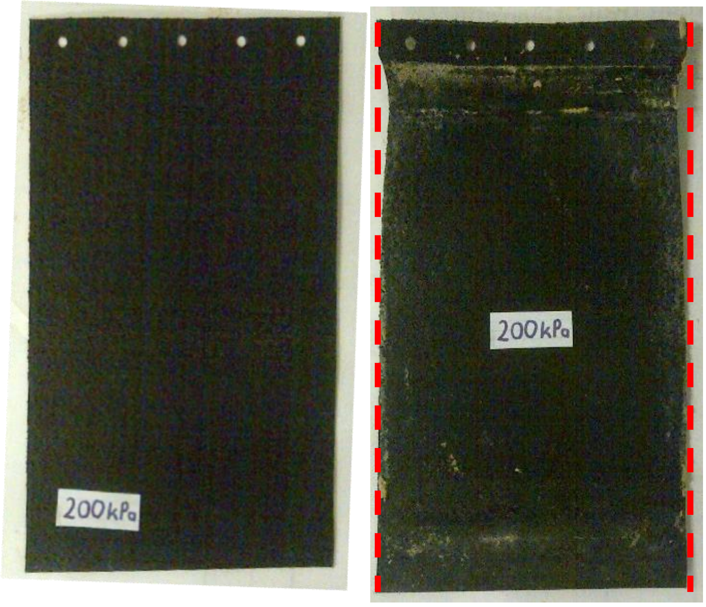

Figure 5: Geomembrane sample before and after testing, showing elongated sample

4 CONCLUSIONS

The study of large direct shear tests conducted on LLDPE and HDPE geomembrane interfaces against various geosynthetics commonly found in landfills, led to the following conclusions:

(1) The formulation of geomembranes influence interface friction parameters thus LLDPE and HDPE geomembranes had different friction characteristics when sheared with different geosynthetics,
(2) Conventional linear failure envelopes did not always give the best regression relationship between shear stress and normal stress parameters for sheared interfaces. Some geomembrane shear strength envelopes could be described more accurately as bilinear failure envelopes.
(3) When a linear failure envelope is considered, at normal stresses less than 150kPa, LLDPE geomembrane peak interface shear stresses were higher than HDPE geomembrane peak shear stresses. Normal stresses greater than 150kPa indicated that HDPE geomembranes had higher peak interface shear stresses when compared to those produced by LLDPE geomembranes
(4) For applications where low normal stresses (<150kPa) would be applied, such as in landfill capping systems, it is recommended to select flexible geomembranes with high interface parameters such as LLDPE geomembranes.
(5) Engineers are recommended to use HDPE geomembranes where large normal stresses would be experienced such as along the base and slopes of a landfill.
(6) It was also evident that the shear resistance between a stiff geotextile on a geomembrane reduced the maximum shear stress achieved at failure.

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