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TECHNICAL NOTE

Shear Strength of Single and Multi-layer Soil–Geosynthetic and Geosynthetic–Geosynthetic Interfaces Using Large Direct Shear Testing

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Abstract

Landfill liners are critical components of waste containment systems that are designed to prevent the migration of pollutants into the environment. Accurate measurement of the shear strength of soil–geosynthetic and geosynthetic–geosynthetic interfaces is essential for designing safe and cost-effective landfill liners. This paper presents a comparative study of the shear strength parameters of single and multi-layer interfaces using a Large Direct Shear Apparatus (LDSA). The study aimed to investigate the effects of using different testing configurations on the Peak and Large Displacement (LD) strengths of the interfaces and to identify the test configuration that provides the most critical shear strength results. A "305 × 305 mm" LDSA was used to perform interface shear tests in saturated conditions with applied normal stresses ranging from 50 to 400 kPa. The results showed good agreement between strength envelopes derived from single and multi-layer interface tests for the materials tested. However, the peak and LD strengths were generally 9% and 24% lower, respectively, for single interface tests than for multi-layer interface tests across the range of normal stresses considered. This conservative estimate may be attributed to the rigid clamping of the geosynthetics, resulting in some tensile strains that reduce the peak and LD shear strengths. Moreover, it was observed in multi-layer interface tests that transfer of shear stresses within the system could have occurred, which could have led to higher overall peak and LD shear strengths. Higher displacements along the critical interface in single interface tests than in multi-layer interface tests may also contribute to this outcome. Overall, these findings have important implications for designing landfill liner systems and performing shear strength tests. Specifically, multi-layer interface tests provide a better simulation of field conditions and a more accurate representation of the shear strength characteristics of composite liner systems. However, performing multiple single interface tests may still be necessary to fully understand the shear strength of individual interfaces. Further research is needed to explore the implications of these findings for other materials and testing conditions.

Keywords Geosynthetics · Large direct shear apparatus · Multi-layer interface test · Single interface test · Shear strength parameters

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Introduction

Solid waste containment systems, such as landfills, frequently use geosynthetics—a wide range of synthetic planar materials made from polymeric material—to protect surface and groundwater from contamination. Composite liner systems in landfills consist of multiple interfaces which include a broad range of geosynthetics in conjunction with soil, rocks, and any other related materials, which results in the introduction of many interface planes into the structure which can potentially create instability especially along the slope, and ultimately result in failure [1–3]. Therefore, appropriate geosynthetic interface and/or internal shear strength should be used during landfill design and construction.

Despite the importance of geosynthetic interface shear strength, there is still uncertainty regarding the ideal interface testing configuration. Many laboratories determine the geosynthetic shear design characteristic values used in the design of structures like landfill liners using single interface testing, rather than multi-layer interface testing. However, only a few studies [4–6] have substantiated and quantified the significance of varying the many possible interface shear testing configurations. This has led to a limited understanding of the shear strength characteristics of composite liner systems. While laboratory tests, such as direct shear, ring-shear, inclined plane, and pull-out device, can be used to determine geosynthetics interface and internal shear strength [5, 7], direct shear is a commonly used device in most laboratories around the world. Therefore, a Large Direct Shear Apparatus (LDSA) was used to compare shear strength testing of single and multiple geosynthetic interfaces in this study.

Shenthan et al. [5] proposed two methods for determining the interface shear strength on a LDSA: (a) single-interface, and (b) multi-layer interface shear tests. According to Stark et al. [7], landfill liners are composed of multiple interfaces, and using single interface shear tests can result in an overestimation or underestimation of the shear strength of certain geosynthetic interfaces. This is a disadvantage as it may lead to slope instability and considerable remedial costs, as highlighted by Stark and Choi [8]. Moreover, a composite liner system comprises numerous interfaces that would necessitate testing. As noted by Sikwanda et al. [4], conducting multiple single interface tests would require a significant investment of time and resources to gain a complete understanding of the shear strength characteristics of the entire liner system. Furthermore, according to Khilnani et al. [6], in single interface testing, the failure surface is constrained to a particular geosynthetic interface which may not accurately reflect the actual field conditions since a composite liner system experiences shear movement on more than one interface plane. On the other hand, multi-layer interface testing, as pointed out by Stark et al. [9], offers the potential to address all of these limitations. This is because in multi-layer interface testing, all interfaces are tested simultaneously, allowing failure to occur along the weakest interface as expected in the field [8]. As a result, designers can obtain a more accurate representation of field conditions.

Many studies [5, 10–14] have made great efforts into studying the geosynthetic interface using single interface tests. However, there are limited publications on the use of multi-layer interface shear testing to determine the geosynthetic interface shear strength. The main objective of this study was to investigate, using a LDSA, the effects of using different testing configurations, single and multi-layer interface, on the Peak and Large Displacement (LD) at soil-geosynthetic and geosynthetic-geosynthetic interfaces. The study presented herein was undertaken to make comparisons between the results obtained from multi-layer interface testing to at least one single interface test to provide information on the most critical interface for the modern landfill configuration shown in Fig. 1. Additionally, it was intended to determine the test configuration that yields the most significant shear strength results and to understand the fundamental mechanisms behind the observed shear strength.

Experimental Materials and Methods

Materials

Two soils and three different types of geosynthetics (Geotextile, Geomembrane and Geosynthetic Clay Liner), that form the critical interface components of a lining system in a modern landfill liner (see Fig. 1), were used to achieve

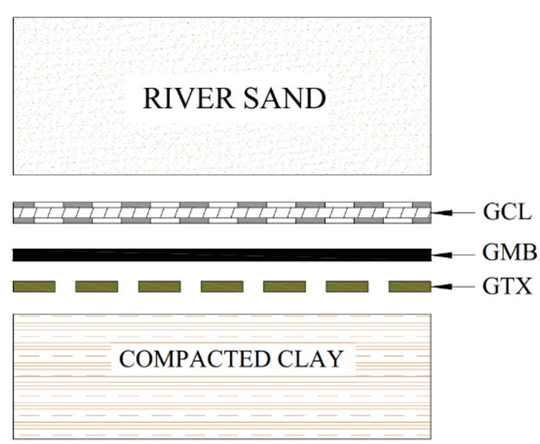

Fig. 1 Schematic of simulated modern landfill configuration

Table 1 Engineering properties of the soils

Soil properties	River sand	Clay
Specific gravity, G_s	2.60	2.80
Cohesion, c' (kPa)	0.00	20.90
Angle of internal friction, ϕ' (°)	43.0	38.70
Optimum moisture content, OMC (%)	11.5	24.30
Maximum dry density, MDD (Mg/m^3)	1.70	1.60
Coefficient of uniformity, C_u	2.40	–
Coefficient of curvature, C_c	1.20	–
Plasticity index, PI (%)	–	30.2

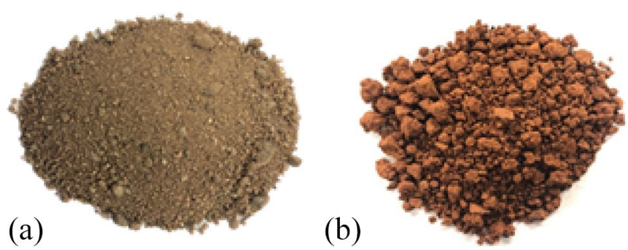

Fig. 2 Selected soils: **a** river sand and **b** clay

the objectives of this study. Each of the materials is subsequently described.

Soil Materials

River sand and *clay* were used in the study. Both soils were consistent and easy to work with, thus making it possible for the results to be repeatable. Table 1 gives the engineering properties of the soils. The river sand is a poorly graded, brownish, fine uniform sand; the clay is a reddish brown, lean clay with sand. Figures 2 and 3 show the two soils and their grading curves, respectively.

Geotextile (GTX)

The bidim® A10 GTX was used in this study, and it is one of the most extensively used in landfill liners in South Africa, thus making it suitable for simulating the anticipated field conditions [15]. This product was selected for this study since it met the minimum requirements, as specified by the Geosynthetic Institute (GSI) to be used as a cushion in a landfill. Moreover, it was manufactured by a local company in Cape Town, South Africa, making it readily available. Table 2 shows the essential properties of the GTX as provided by the manufacturer.

Geomembrane (GMB)

The GMB used in the study was a 2 mm thick black double textured HDPE with an average surface asperity height of 0.80 mm on one side (minor spikes) and 1.80 mm on the other side (major spikes). This product was factory-made from HDPE resin under controlled conditions. This GMB was specifically selected because it is the most popular GMB used in landfill applications in South Africa [15]. Table 3 shows the fundamental properties of the GMB.

Fig. 3 Grading curves for river sand and clay

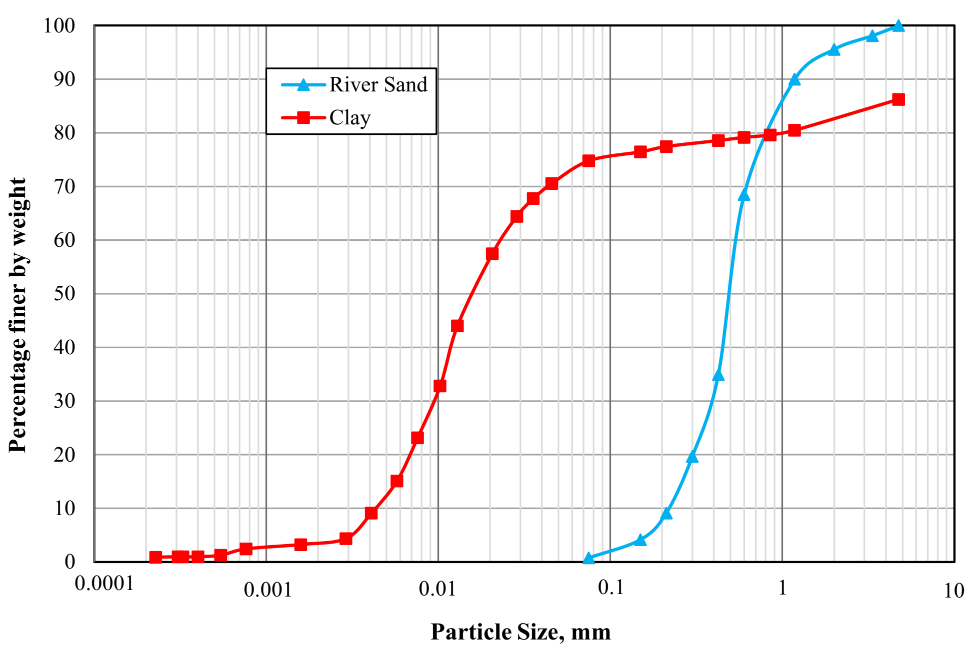

Table 2 Fundamental GTX properties

Properties[a]	Units	MARV	Test method
Mass per unit area	g/m^2	1080	ASTM D5261
Thickness	mm	6.4	SANS 9863
Grab tensile strength	kN	3.70	ASTM D4632
Grab tensile elongation	%	50–80	
Trapezoidal tear strength	kN	1.95	ASTM D4533
Punctured (CBR) strength	kN	11	SANS 12236
Permeability	m/s	0.0026	SANS 11058
Pore size, $O_{95\ W}$	µm	< 75	SANS 12956

MARV minimum average roll value

[a]Curtesy of Kaytech Engineered Fabrics

Table 3 Fundamental GMB properties.

Properties	Units	MARV	Test method
Formulated density[a]	g/cm^3	≥ 0.94	ASTM D1505-18
Carbon black content[a]	%	2.5	ASTM D4218-20
Tear resistance[a]	N	249	ASTM D1004-21
Puncture resistance[a]	N	534	ASTM D4833/D4833M-07
UV resistance[a]	%	50	ASTM D5885/D5885M-20

MARV minimum average roll value

[a]AKS Lining Systems (2020)

Table 4 Fundamental GCL properties

Properties	Units	MARV	Test method
GCL mass per unit area	g/m^2	4210	ASTM D5993
Grab strength (both directions)	N	1500	ASTM D4632
	N	1500	
CBR burst	N	2500	ISO 12236
Bentonite layer (at 0% moisture content	ml/2 g	≥ 24	ASTM D5890

MARV minimum average roll value

[a]Curtesy of Kaytech Engineered Fabrics

Geosynthetic Clay Liner (GCL)

The reinforced GCL used in this study was made up of a white polypropylene Non-Woven (NW) GTX cover on top, underlain by a light brown, dry sodium bentonite powder layer in the middle and overlain by a polypropylene slit film Woven (W) GTX carrier layer. This needle punched GCL was chosen because it is the most common type of reinforced GCL used in Landfills in South Africa. The use of GCLs in landfill liners as a substitute for traditional compacted clay has become common practice [15]. The fundamental properties of the GCL are given in Table 4.

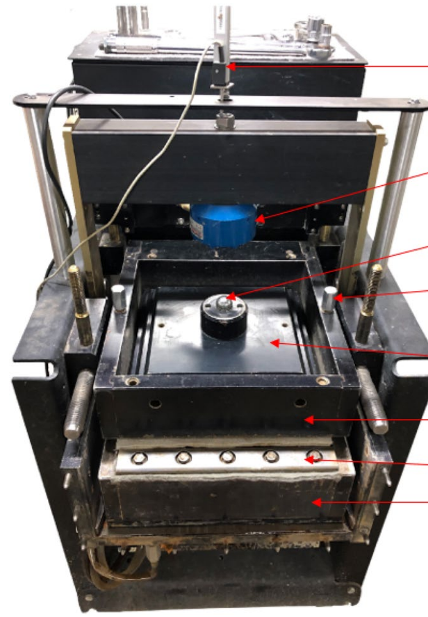

Fig. 4 ShearTrac-III large direct shear apparatus

Test Apparatus

The interface shear tests were carried out in the Geotechnical Engineering Laboratory at the University of Cape Town, South Africa, using the free-standing *ShearTrac-III* Large Direct Shear Apparatus (LDSA) shown in Fig. 4. The equipment consists of a top (static) shear box with plane dimensions of 305 × 305 mm and a depth of 100 mm, and a lower (moving) shear box with plane dimensions of 460 × 355 mm and a depth of 100 mm.

Test Procedures

The geosynthetic test samples were randomly cut from supplied rolls and sized to fit either the top or bottom shear box of the LDSA. The specimens were cut to 300 × 325 mm and 300 × 450 mm for the top and bottom boxes, respectively, using a standard template available in the laboratory. The tests were conducted at normal stresses of 50, 100, 200, and 400 kPa to represent the varying load conditions experienced by the liner system during the design life of a landfill. The applied methodology and parameters were chosen based on recommendations by previous studies [4, 14, 16]. The test configurations for both single and multi-layer interface tests are briefly summarized below.

Single interface tests were conducted by fastening one specimen to the bottom box and the other to the top box to determine the shear strength of the geosynthetic–geosynthetic interfaces. To determine the shear strength of the soil–geosynthetic interfaces, the soil specimen was compacted in the lower box, while the geosynthetic specimen was clamped to the top box. Similar configurations as to those adapted for single interface tests were used to set up multi-layer interface tests. Multi-layer interface tests were carried out as double or triple interface tests, with each test consisting of either two or three geosynthetic specimens, respectively. The geosynthetic specimens were placed unclamped between the top and bottom shear boxes so as to allow failure to occur at the weakest interface during shearing. The specimen configuration followed for both single and multi-layer interface tests are shown in Fig. 5, following the standards of ASTM D5321 [17] and ASTM D6243 [18].

The *Shear Trac-III* device was set up and the vertical load cell was properly aligned. The Shear Displacement Rate (SDR) was set to 1 mm/min for the interface tests that did not involve GCLs or clay specimens, a consolidation and hydration period of 1 h. For all other interface tests involving clay or GCL samples, a recommended SDR of 0.1 mm/min was used, along with a consolidation and hydration period of 24 h. These SDRs were applied to reflect field applications and to ensure that excess pore pressure does not accumulate significantly during failure. Additionally, the consolidation times were anticipated to be sufficient for the gripping surfaces to completely engage with the test samples and for the excess pore pressure to drop to zero before shearing began. Once consolidation and hydration were completed, a sufficient gap of approximately 1–5 mm was created between the top and bottom shear boxes. The shear device was calibrated, and the shear test was initiated.

During the shear test, the bottom section of the shear box moved at a user-specified shear rate in relation to the top static shear box. Vertical displacements and shear responses were captured and stored on a computer during the shearing phase by the Linear Variable Differential Transducer (LVDT) and load cell, respectively. To ensure that all tests were conducted up to standard, measures were implemented in each test. The testing procedures and results in this study were verified for repeatability by performing at least two replicate tests of both single and multi-layer interface tests with more detailed information on the repeatability of the tests results available in Muluti [19].

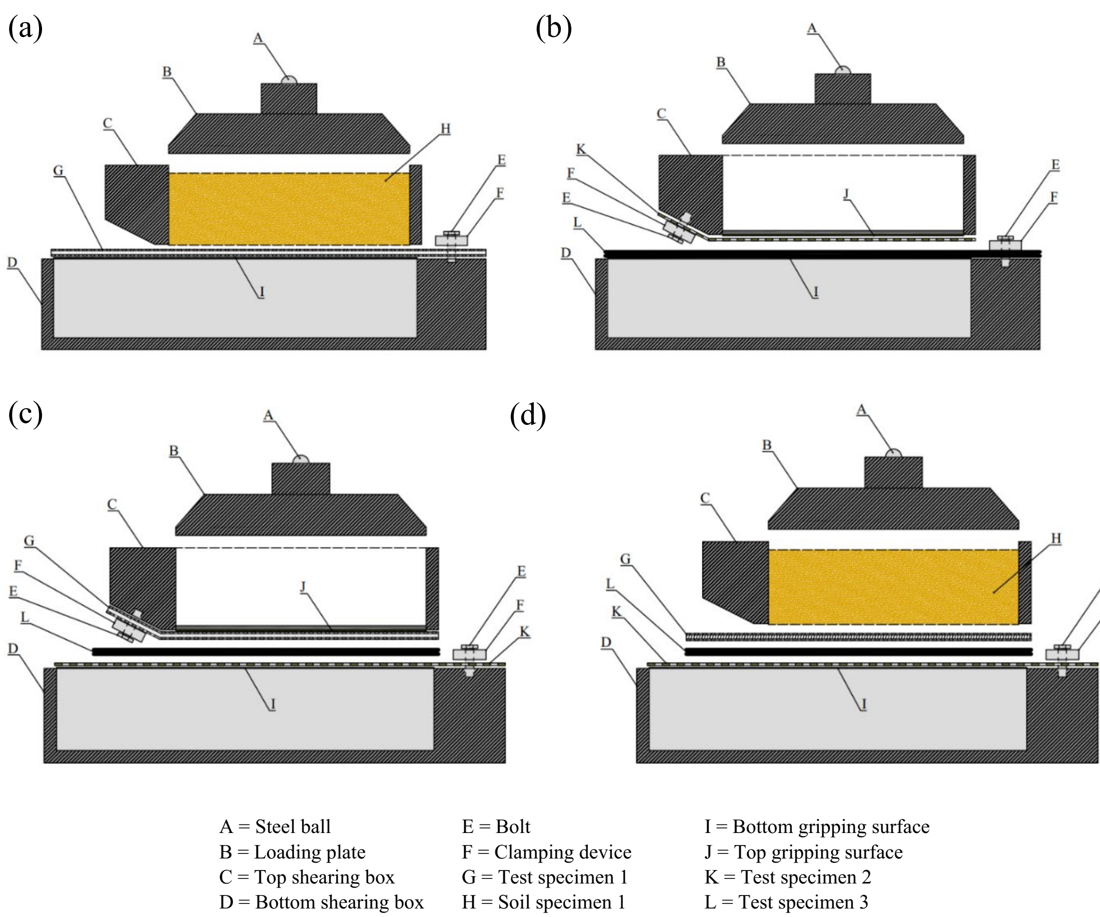

Fig. 5 Test sample configuration for single and multi-layer interface testing: **a** soil–geosynthetic and **b** geosynthetic–geosynthetic, **c** geosynthetic–geosynthetic–geosynthetic and **d** soil–geosynthetic–geosynthetic–geosynthetic

Results and Discussion

Shear Stress Versus Horizontal Displacement

Single Interface Tests

Figure 6 presents the typical results of single interface tests at applied normal stresses of 50, 100, 200, and 400 kPa, showing the relationship between shear stress and horizontal displacement. In all cases, the shear stress increased with displacement until reaching a maximum (peak) interface shear strength. However, one notable difference between soil–geosynthetic and geosynthetic–geosynthetic interface tests was the relative shape of the curves. For the CLAY–GTX interface, the stress–displacement curve displayed a gradual initial rise and limited change after the peak strength had been mobilized. This behavior is due to the interlocking and shearing of soil particles within the geosynthetic material, resulting in a reduction in shear strength with increasing displacement. The results were consistent with past literature by [10, 12, 20, 21] on soil/geosynthetic interface tests. In contrast, the GTX-GMB interface exhibited a rapid initial rise and a well-defined peak, followed by a fast reduction in shear strength until reaching a state of large displacement (LD). This behavior was possibly due to strain-softening, a process associated with dislocation movements within the crystal structure of the tested specimens, which became more pronounced with increasing applied normal stress [15]. The geosynthetic materials tended to deform and interlock with each other, leading to a relatively constant shear strength with increasing displacement, which was consistent with previous findings by [13, 14, 22–25].

Moreover, the curves in Fig. 6c showed distinct pre-peak stresses at all normal stresses, which can be described as a '*skew*' behavior at various horizontal displacements. This phenomenon has been observed by previous researchers and attributed to the interaction between the test samples and the gripping surface (sandpaper) [24, 26]. Similar '*skew*' behavior was observed for the third and fourth

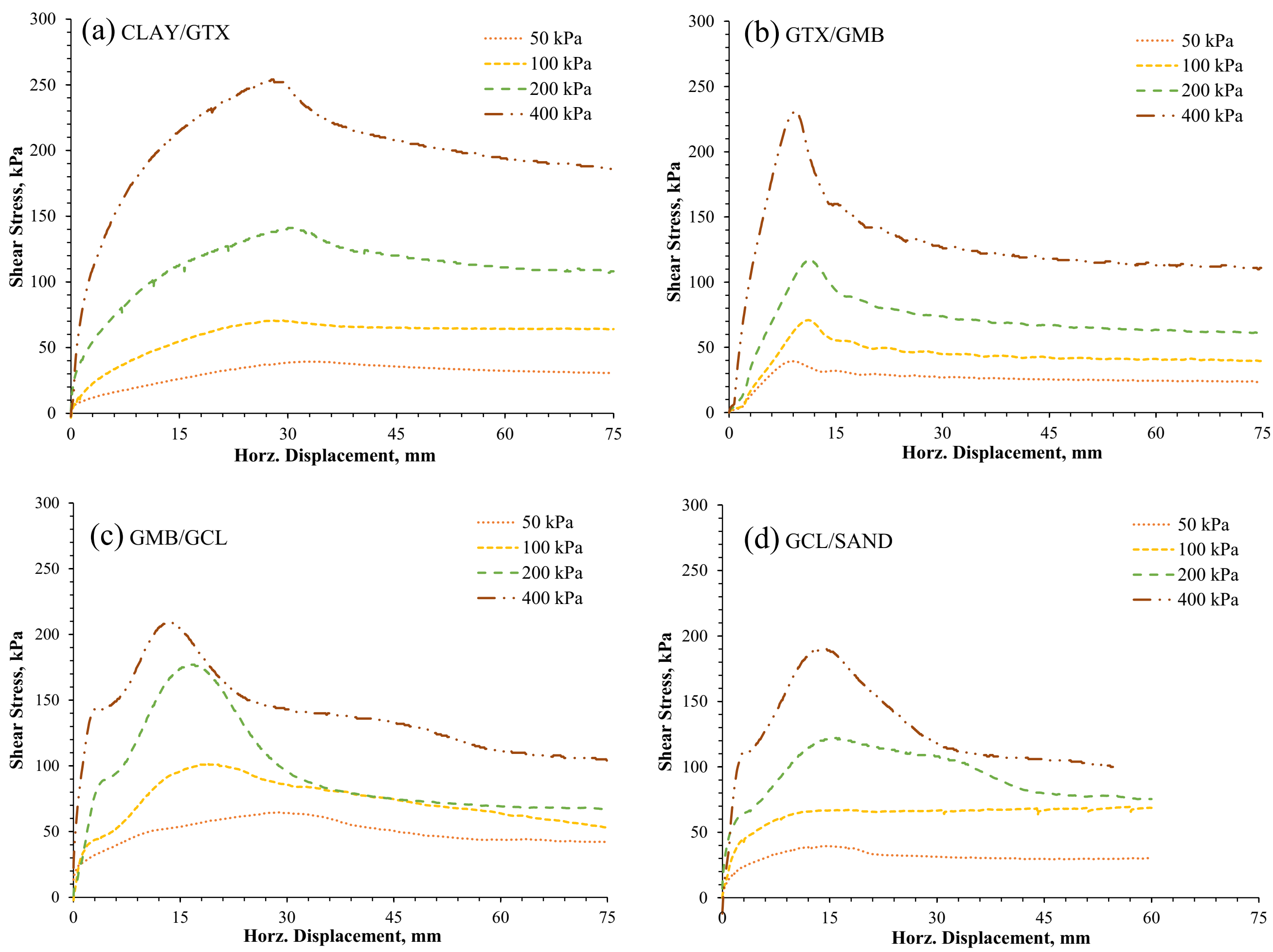

Fig. 6 Shear stress—horizontal displacement results for single interface tests

applied normal stress of the GCL-SAND Interface, as shown in Fig. 6d.

Multi-layer Interface Tests

It can be observed from Fig. 7 that the measured shear stress responses for all multi-layer interface tests were non-linear

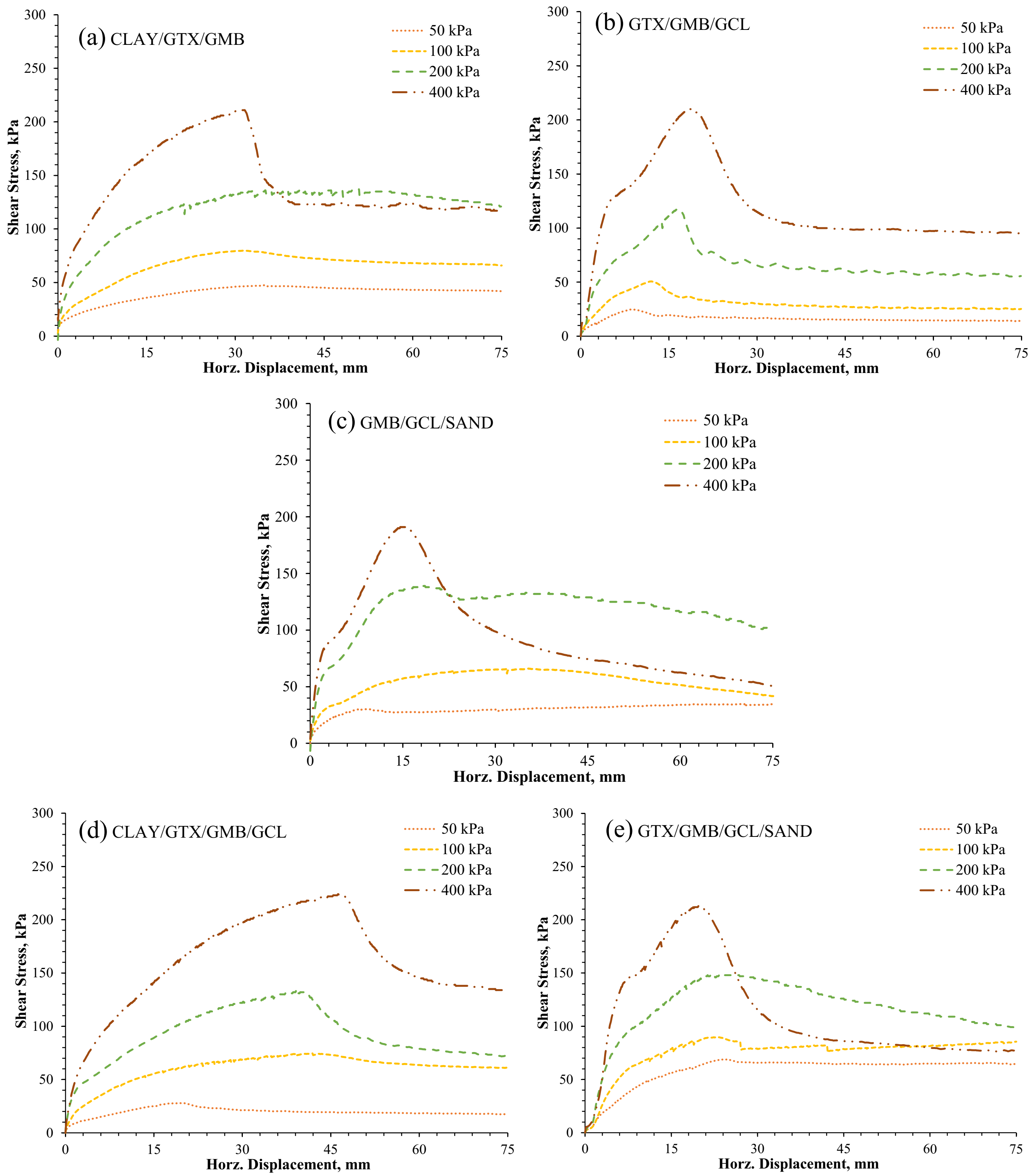

Fig. 7 Shear stress—horizontal displacement results for multi-layer interface tests

for all the normal stresses applied. Shear stress increased with an enhancement in shear displacement for all plots at the maximum normal stress of 400 kPa, showing a 'smooth' pre-peak intensity behavior before reaching a peak value. However, once the peak strength was mobilized, the shear stress dropped rapidly as horizontal shear displacement increased, bringing the shear stress closer to the LD shear strengths. The transfer of shear stress within the system may have possibly caused this "rapid" decrease in shear stress after pre-peak behavior. Shearing was expected to occur along the weakest or critical interface, as is usually the case in single interface tests. As a result, once the pre-peak strength was mobilized, the shear stress could have been transferred from one interface to another, resulting in the rapid reduction in shear stress at the post-peak stage.

However, for all multi-layer interface tests the interface shear behavior observed at lower stresses of 50 and 100 kPa can be characterized by little to no post-peak shear strength softening or reduction. The strain-softening difference observed may possibly be due to the normal stress applied, with strain-softening increasing as the applied normal stress augmented. As a result, the strain-softening behavior was related to the dislocation movements produced within the crystal structure of the tested soil and the geosynthetic specimens [15].

Failure Envelope and Critical Interfaces

The respective peak and LD interface shear stresses were obtained from the single and multi-layer interface tests and are presented in Tables 5 and 6. From the peak and LD shear stress values obtained, failure envelopes were generated using a line of best-fit for each single and multi-layer interface. However, after further study, it was discovered that multi-linear (that is bilinear) or non-linear (that is curvilinear) models could better reflect failure envelopes. As a result, for both single and multi-layer interfaces, all best-fit straight lines (dashed lines) with linear regression (R^2) of less than 0.98 were represented with multi-linear and non-linear failure envelopes (solid lines), and more detailed information on the non-linear equation can be found in Muluti [19]. Multi-layer interface failure envelopes were also compared to combination peak and LD strength failure envelopes. These were created by combining segments of single interface shear strength envelopes that represented the lowest peak and LD strength for a range of normal stresses to determine the most critical interface.

Single Interfaces

Figure 8 shows that linear failure envelopes were best suited ($0.98 \leq R^2 \leq 1$) in just 37.5% of the tests, while curvilinear failure envelopes were best expressed in about 50% of the tests, and only 12.5% best-exhibited bilinear envelopes. As the normal stresses applied increased, the weakest interface was transferred between the different interfaces tested. The peak and LD shear strength parameters in terms of interface friction angle (δ) and apparent cohesion (c_a) from the linear failure envelopes were determined for the four single interfaces. They are summarized in Table 7.

Table 5 Summary of peak and LD strength for single interface tests

Normal stress (kPa)	Single-interfaces							
	CLAY/GTX		GTX/GMB		GMB/GCL		GCL/SAND	
	Peak (kPa)	LD (kPa)	Peak (kPa)	LD (kPa)	Peak (kPa)	LD (kPa)	Peak (kPa)	LD (kPa)
50	39.4	30.4	39.3	23.5	64.7	42.5	39.4	30.2
100	70.7	64.1	70.9	39.6	102.0	53.3	69.4	68.7
200	141.0	108.0	117.0	61.2	177.0	67.6	122.0	75.4
400	254.0	187.0	231.0	111.0	209.0	104.0	190.0	100.0

Table 6 Summary of peak and LD strength for multi-layer interface tests

Multi-layer Interfaces	Normal stress (kPa)									
	CLAY/GTX/GMB		GTX/GMB/GCL		GMB/GCL/SAND		CLAY/GTX/GMB/GCL		GTX/GMB/GCL/SAND	
	Peak (kPa)	LD (kPa)	Peak (kPa)	LD (kPa)	Peak (kPa)	LD (kPa)	Peak (kPa)	LD (kPa)	Peak (kPa)	LD (kPa)
50	47.4	41.9	24.7	14.3	34.6	34.4	28	17.5	68.8	64.6
100	79.7	65.9	50.7	25.3	66	41.7	74.5	61.2	89.7	85.5
200	137	121	117	55.7	139	100	133	72.5	149	98.7
400	211	117	210	95.8	191	50.6	224	134	213	77.2

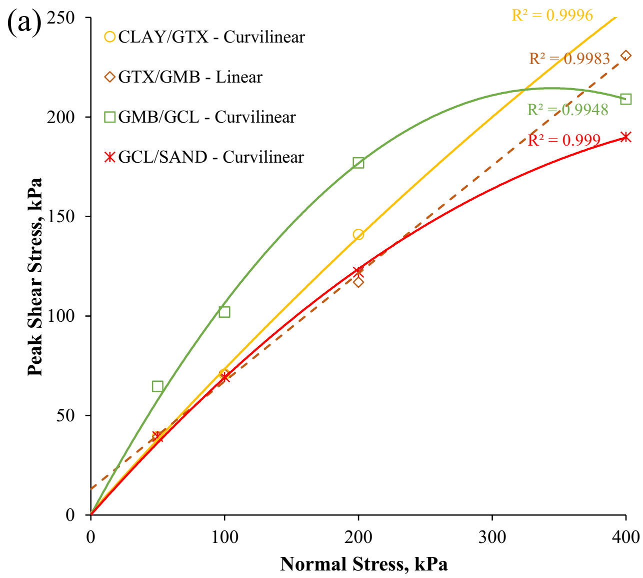

Fig. 8 Failure envelopes for single interfaces: **a** peak and **b** LD shear stress

Table 7 Summary of shear strength parameters for single interfaces

Interface configuration	Peak		LD	
	δ_p (°)	$c_{a\text{-}p}$ (kPa)	δ_{LD} (°)	$c_{a\text{-}LD}$ (kPa)
CLAY/GTX	31.5	11.1	23.5	15.7
GTX/GMB	28.4	13.0	13.8	12.8
GMB/GCL	21.8	63.0	9.8	34.4
GCL/SAND	22.9	25.9	9.5	37.2

Table 7 shows that the CLAY-GTX interface had the highest peak and LD friction angles as compared to the other three single interfaces. As a result, this interface was deemed to be the strongest. For this interface, the peak and LD interface friction angles were 31.5° and 23.5°, respectively. The GMB-GCL and GCL-SAND interfaces, on the other hand, had the lowest peak and LD friction angle, making them the weakest interfaces of all the single interfaces tested.

Multi-layer Interfaces

It can be observed in Fig. 9 that the linear failure envelopes accounted for about 40% of the tests, while curvilinear failure envelopes were best expressed in about 45% of the tests, and only 15% best-exhibited bilinear envelopes. The peak and LD combination strength envelope from the single interface tests is compared with the corresponding combination peak and LD strength envelopes from the respective multi-layer interface tests. From Fig. 9, it was observed that for the combination failure envelopes from single interface tests, the peak strengths are slightly lower for the range of normal stresses considered, particularly at low normal stresses. This difference may be attributed to isolated single interface tests that were not affected by the surrounding geo-synthetics. The peak and LD shear strength parameters from the linear failure envelopes for both single and multi-layer interfaces are summarized in Table 8.

It was evident from Table 8 that the interface peak friction angles from the respective combination failure envelopes and the failure envelopes for the multi-layer interfaces were comparable. The percentage difference in interface friction angle between the failure envelopes for all the respective interface configurations ranged between 1 and 15%. The combination envelopes from the single interfaces for all the multi-layer interfaces showed lower peak interface friction angles compared to the failure envelopes obtained from the respective multi-layer interface tests, except for the CLAY/GTX/GMB and GTX/GMB/GCL/SAND interfaces. For instance, for the GTX/GMB/GCL interface envelope peak friction angle of 28.0° was achieved, whereas the combination envelope achieved a peak friction angle of 25.5°. The percentage difference for the GTX/GMB/GCL interface envelope and combination envelope was 9.0%.

On the other hand, the combination envelopes from the single interfaces for all the multi-layer interfaces showed higher peak interface friction angles compared to the failure envelopes obtained from the respective multi-layer interface tests, except for the GTX/GMB/GCL and CLAY/GTX/GMB/GCL interfaces. This variation in shear strength behavior is consistent with the finding of [9]. This suggests that the interface shear strengths of geosynthetics considered in this study can be influenced by the gripping and clamping systems used in the experiment and the test configuration, which is single or multi-interface. Based on these

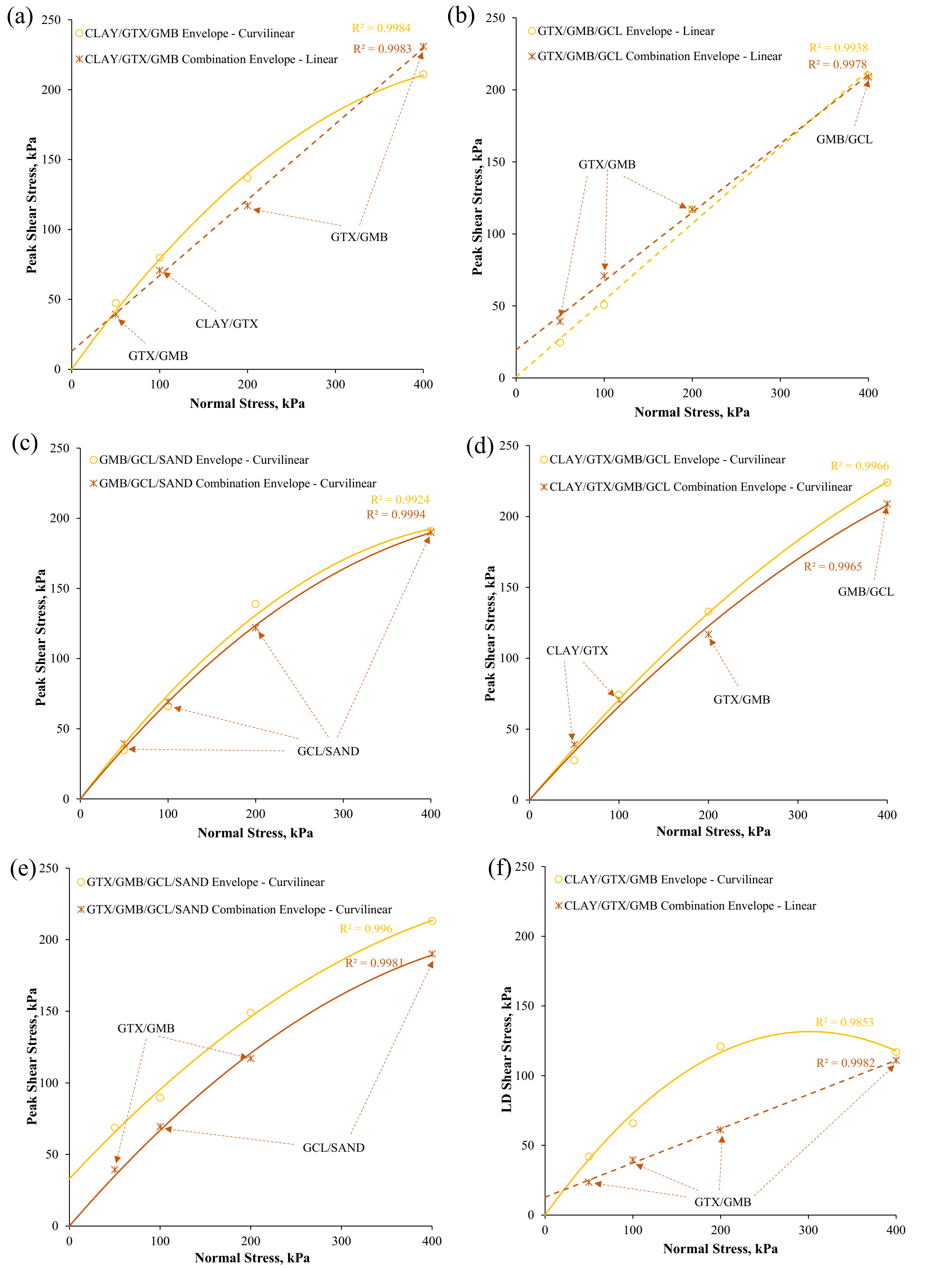

Fig. 9 Failure envelopes for multi-layer interfaces: (**a**–**e**) peak and (**f**–**j**) LD shear stress

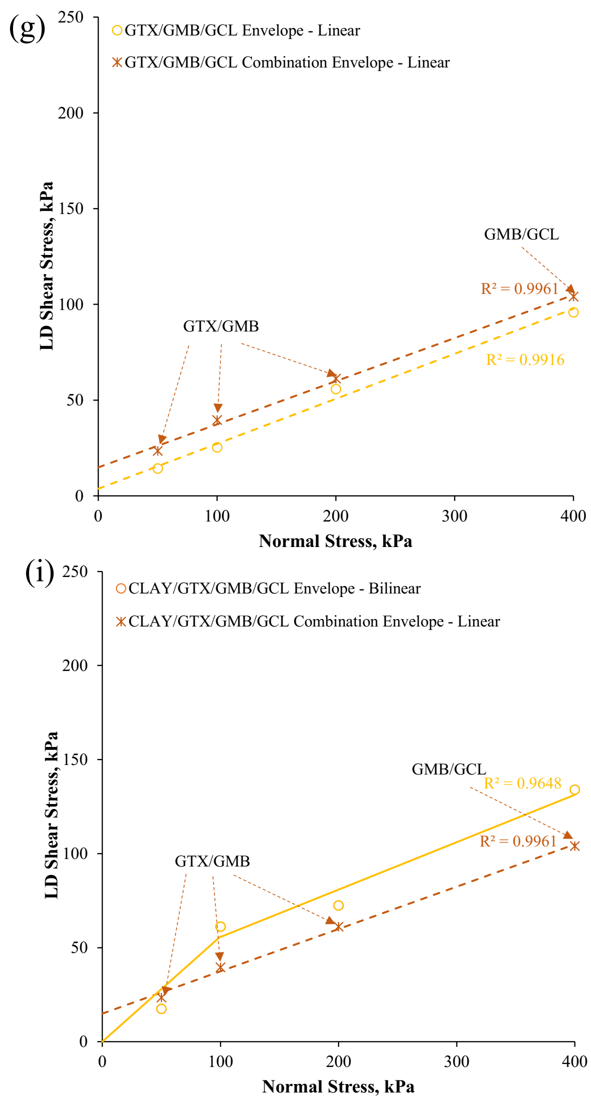

Fig. 9 (continued)

observations, it can be said that the combination envelopes obtained from the respective single interfaces yielded a conservative estimate of the peak and LD interface shear strength values, as compared to the multi-layer interfaces.

Conclusions

A series of direct shear tests using various test configurations, single and multi-layer interfaces, were conducted using the *ShearTrac-III* large direct shear apparatus of 305 × 305 mm box size. Key information on the importance of using one test configuration (single interface), as opposed to the other (multi-layer interface), was provided by the analysis of the results in determining the geosynthetic shear strength characteristics of each respective interface. From the results presented in this paper, the following conclusions were drawn:

1. Regardless of the normal stress applied, conventional soil–geosynthetic and geosynthetic–geosynthetic shear stress versus shear displacement responses with non-linear behavior were observed in both single and multi-layer interface tests.
2. The relative shape of the curves for soil–geosynthetic interfaces were found to be different from the curves for geosynthetic–geosynthetic interface tests. The stress-displacement curves for soil–geosynthetic interface tests showed a steady initial increase in shear stress and a minimal change in peak strength mobilized. The stress-displacement curves for the geosynthetic–geosynthetic interfaces, on the other hand, showed a rapid initial

Table 8 Summary of peak and LD shear strength parameters for multi-layer interfaces

Interface configuration	Peak		LD	
	δp (°)	$c_{a\text{-}p}$ (kPa)	δ_{LD} (°)	$c_{a\text{-}LD}$ (kPa)
CLAY/GTX/GMB				
Envelope	24.7	32.5	11.7	47.7
Combination envelope	28.5	12.9	13.8	12.8
GTX/GMB/GCL				
Envelope	28.0	0.8	13.2	3.8
Combination envelope	25.5	19.7	12.7	14.9
GMB/GCL/SAND				
Envelope	23.9	24.7	2.9	47.2
Combination envelope	22.9	25.9	10.5	28.1
CLAY/GTX/GMB/GCL				
Envelope	28.4	13.41	16.7	14.9
Combination envelope	25.5	19.6	12.7	14.9
GTX/GMB/GCL/SAND				
Envelope	22.5	52.3	1.0	78.2
Combination envelope	22.9	24.7	12	16.1
CLAY/GTX/GMB/GCL/SAND				
Envelope	16.3	47	1.5	40.7
Combination envelope	22.9	24.7	12	16.1

increase in shear stress with a well-defined peak, followed by a rapid decrease in shear strength after the peak shear stress was reached. The surface texture of the GMBs used in all of the geosynthetic–geosynthetic interface experiments possibly contributed to this finding.

3. The high shear strength obtained in single interface tests could be due to the clamping that confined each of the test specimens to one end of the shear block during shearing. However, in multi-layer interface tests, only the top and bottom test specimens were clamped, leaving the middle test specimens unconfined. As a result, depending on which plane was the weakest, failure may have occurred at any of the available interfaces.
4. The findings revealed that there may have been a transfer of shear stresses within the system when conducting the multi-layer interface shear tests once the system began to shear, regardless of the various multi-layer interface configurations used.
5. Therefore, for the interfaces tested here, single interface tests yielded a conservative estimate of peak and LD strength. This may be due to the greater displacement along with the critical interface in single interface tests than in multi-layer interface tests, as indicated by Stark et al. [7].

Future Research

Since only one type of geosynthetic specimen has been tested, the data from these results are limited to the scope of this study. As such additional testing is required using other different types of geosynthetics to present a full comparison of single and multi-layer interface tests. Moreover, additional tests should be performed using different recommended large direct shear devices, which is 1.0 m × 1.0 m, to reduce boundary effects. The findings from these tests should then be compared with the respective results obtained in this research.

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Data Availability Statements The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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