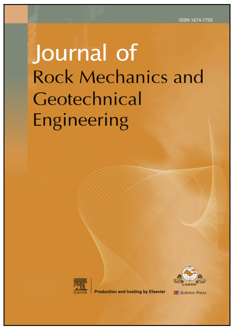

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Shear strength behavior of geotextile/geomembrane interfaces

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Abstract: This paper aims to study the shear interaction mechanism of one of the critical geosynthetic interfaces, the geotextile/geomembrane, typically used for lined containment facilities such as landfills. A large direct shear machine is used to carry out 90 geosynthetic interface tests. The test results show a strain softening behavior with a very small dilatancy (<0.5 mm) and nonlinear failure envelopes at a normal stress range of 25–450 kPa. The influences of the micro-level structure of these geosynthetics on the macro-level interface shear behavior are discussed in detail. This study has generated several practical recommendations to help professionals to choose what materials are more adequate. From the three geotextiles tested, the thermally bonded monofilament exhibits the best interface shear strength under high normal stress. For low normal stress, however, needle-punched monofilaments are recommended. For the regular textured geomembranes tested, the space between the asperities is an important factor. The closer these asperities are, the better the result achieves. For the irregular textured geomembranes tested, the nonwoven geotextiles made of monofilaments produce the largest interface shear strength.

Keywords: geotextiles; geomembranes; landfills; fiber length; roughness; shear strength; friction angle

1. Introduction

The main functions of a municipal solid waste (MSW) landfill are to permit the maximum accumulation of waste in the smallest possible space and to isolate the waste from the natural surroundings. Besides, a MSW has to maintain security and provide a future usage after its closure. Landfill liner and cover systems are mainly formed by geosynthetic protection layers, which interact on geosynthetic/geosynthetic and geosynthetic/soil interfaces.

An important subject with respect to the landfill stability is the interface shear strength, which has been investigated thoroughly in the last decade (e.g. Fox and Kim, 2008; McCarney et al., 2009; Palmeira, 2009; Eid, 2011; Fox and Ross, 2011; Brachman and Sabir, 2013; Thielmann et al., 2013).

The geotextile/geomembrane interfaces can be used for both liner and cover systems of the landfills. Geomembranes are typically used as a hydraulic barrier and geotextiles protect it from damages that may occur in some situations, such as high normal stresses and angular soil particles. Geotextile/geomembrane interfaces have previously been studied by Giroud et al. (1990), Koutsourais et al. (1991), Giroud and Darrasse (1993), Gilbert and Byrne (1996), Stark et al. (1996), Jones and Dixon (1998), Wasti and Özdüzgün (2001), Hebeler et al. (2005), Bergado et al. (2006) and Pintanga et al. (2009).

The objective of this paper is to study the interface shear behavior of the geotextile/geomembrane, providing a deeper understanding of how the structure of these geosynthetics at a micro-level influences the interface shear behavior at a macro-level. The interface shear behavior is studied by means of the direct shear tests on 18 different interfaces using 8 different geosynthetic materials. The guidelines of ASTM D5321 (2014) are followed during the direct shear test on different types of geosynthetic interfaces. The means to grip the different geosynthetics and the suitable test parameters (shear displacement rate, consolidation time, hydration time) are established based on the studies from Stark and Poeppel (1994), Stark et al. (1996), Fox et al. (1997, 1998), Gilbert et al. (1997), Jones and Dixon (1998), Eid et al. (1999), Triplett and Fox (2001), Zornberg et al. (2005), Sharma et al. (2007) and McCartney et al. (2009). The following relationships are analyzed in this study: interface shear strength vs. shear displacement, shear displacement vs. normal displacement, and interface shear strength vs. normal stress.

This paper provides a useful and practical application for both researches and practitioners who use these materials in the field, helping them to make a decision about what geosynthetic material could work better in a particular loading condition.

2. Experimental work

2.1. Materials

The characteristics of geosynthetics used for the direct shear tests are listed in Table 1 and described as follows:

(1) Three nonwoven geotextiles: GT1 (500 g/m^2) is made of needle-punched monofilaments; GT2 (500 g/m^2) is made of needle-punched staple fibers; and GT3 (335 g/m^2) is made of thermally bonded monofilaments.
(2) Five geomembranes of 1.5 mm thickness: GMs has smooth surfaces; GMr1 and GMr4 have irregular heavy textured surfaces smaller than 1 mm; GMr2s1 and GMr3 show regular, evenly spread asperities greater than 1 mm; GMr2s2 exhibits regular spread asperities smaller than 1 mm.

Table 2 summarizes the geotextile/geomembrane interfaces tested as well as the testing conditions.

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Table 1. Type of geosynthetics.

Geosynthetic	Label	Type	Raw material/Type of fiber	Manufacturing process	Mass/area (g m^{-2})	Density (g m^{-3})	Thickness (mm)[a]
Geotextiles	GT1	NW	PP/monofilament	Needle-punched	500		4±0.2
	GT2	NW	PP/staple fibers	Needle-punched	500		5±0.6
	GT3	NW	70% PP+30% PE/monofilament	Thermally bonded	335		2±0.2
Geomembranes	GMr1	Textured (~0.5 mm)[b]	HDPE	Coextrusion nitrogen gas		≥0.94	1.5
	GMr2	Textured (s1: ~1.2; s2: ~0.8)[c]	HDPE	Calendared structured		≥0.94	1.5
	GMr3	Textured (~1.3)[b]	HDPE	Structured same resin as base		0.94	1.5
	GMr4	Textured (~0.25)[b]	HDPE	Coextrusion nitrogen gas		≥0.93	1.4
	GMs	Smooth	HDPE	Flat sheet extrusion		0.94	1.5

Note: [a] Thickness at 2 kPa for geotextiles, at 20 kPa for geomembranes; [b] Average asperity height (mm); [c] Average asperity height of GMr2, which presents two different textured sides: s1=side 1 and s2=side 2; NW=Nonwoven geotextile; PP=Polypropylene; PE=Polyethylene; HDPE=High density polyethylene.

Table 2. Geosynthetic interfaces tested and testing conditions.

Geosynthetic interfaces	Sample size (mm×mm)	Normal stress (kPa)	Direct shear test conditions
GT1/GMs, GT1/GMr1, GT1/GMr2s1, GT1/GMr2s2, GT1/GMr3, GT1/GMr4, GT2/GMs, GT2/GMr1, GT2/GMr2s1, GT2/GMr2s2, GT2/GMr3, GT2/GMr4, GT3/GMs, GT3/GMr1, GT3/GMr2s1, GT3/GMr2s2, GT3/GMr3, GT3/GMr4	300×285	25, 50, 100, 300, 450	Tests are conducted under wet conditions: (1) Hydration time: 24 h for geotextile, and 0 h for geomembrane; (2) Consolidation time: 10 min; (3) Shear rate: 5 mm/min

2.2. Testing equipment

The tests on geosynthetics are carried out with a large direct shear machine, whose shear box is 300 mm long and 300 mm wide and therefore fulfills the minimum requirements. The tests are performed at a constant shear displacement rate and fixed normal stress. The shear box is divided into a moving lower part and a static upper part. The geotextile is fastened to the lower box, while the geomembrane is fastened to the upper box. The following gripping systems are used for the different types of geosynthetics:

(1) Geotextiles are gripped with a double-side adhesive tape. This system works well for the range of normal stresses tested.

(2) Based on the studies of Fox et al. (1997, 1998), a particularly textured plate is designed for gripping the drainage geocomposites, the geomembranes and the geosynthetic clay liner (GCL). The dimensions of this plate are 300 mm × 285 mm × 10 mm. The plate has 210 drainage holes of 2 mm diameter and 1680 pyramids of 1 mm height, which protrudes from the topside, as shown in Fig. 1a. The bottom side has channels to allow for water flow, as shown in Fig. 1b. This plate is screwed onto a metal support that is placed into the direct shear box. The topside is in contact with the geosynthetic and the bottom side is in contact with the metal support.

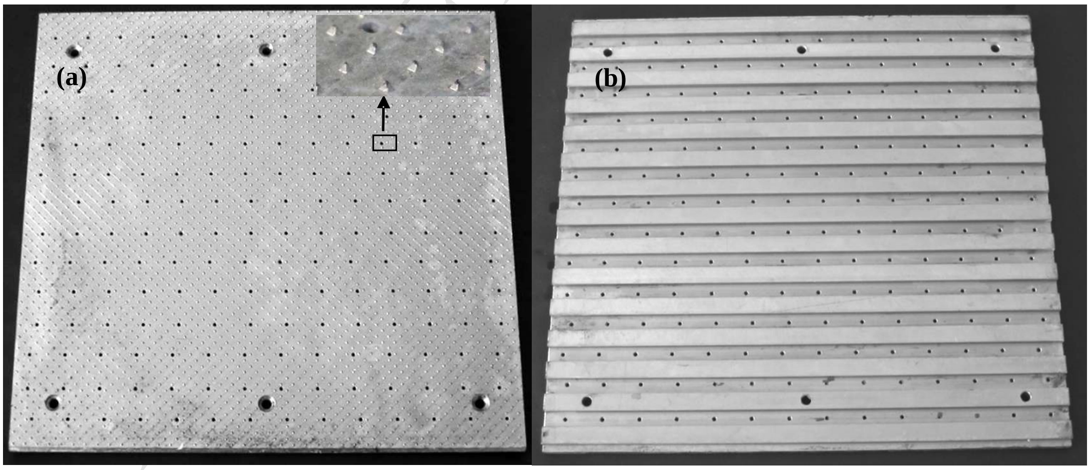

Fig. 1. Textured plate for gripping textured geomembranes. (a) Topside and (b) Bottom side.

2.3. Test procedure

The shear test is carried out according to ASTM D5321 (2014). The geotextile/geomembrane interfaces are tested under wet conditions with the following parameters:

(1) Hydration time is 24 h for the geotextiles and the geomembranes were not hydrated. The geotextile samples are submerged into tap water inside a humidity chamber (temperature of 21 °C, humidity of 96%).

(2) Consolidation time inside the machine is 10 min.

(3) Constant shear rate is 5 mm/min. Stark et al. (1996) and Triplett and Fox (2001) found out that the shear rate does not significantly affect the peak and post-peak strengths.

The normal stress is applied to the loading platen above the upper metal support. After 10 min of consolidation, the lower shear box moves in parallel direction to the shear force at a constant shear rate. The maximum shear displacement is 50 mm. The shear displacement, shear force and vertical displacement are recorded during the test. The shear force is measured using a suitable dynamometric ring. Two linear variable differential transformers (LVDTs) are used to measure the shear and vertical displacements.

3. Constitutive model on geosynthetic interfaces

All interfaces tested exhibit frictional behavior, which is modeled by Mohr–Coulomb's equation $\tau = c_a + \sigma_n \tan\delta$, where τ and σ_n are the interface shear strength and normal stress acting on the failure plane, respectively; c_a is the adhesion; and δ is the interface friction angle. Linear regression of the plot of τ vs. σ_n is used to identify the best-fit shear strength parameters. The shear strength of most interfaces tested in this study presents important friction angles and negligible adhesion.

4. Direct shear test results

As mentioned above, the geotextile/geomembrane interfaces are tested under wet conditions (Table 2). However, the water content does not affect significantly the interface shear strength, as shown in Fig. 2 as well as proven by Mitchell and Mitchell (1992) and Bergado et al. (2006). The range of normal stresses applied is 25−450 kPa. The peak interface shear strength is usually reached at shear displacement of 4−10 mm and the post-peak strength is obtained at shear displacement around 50 mm.

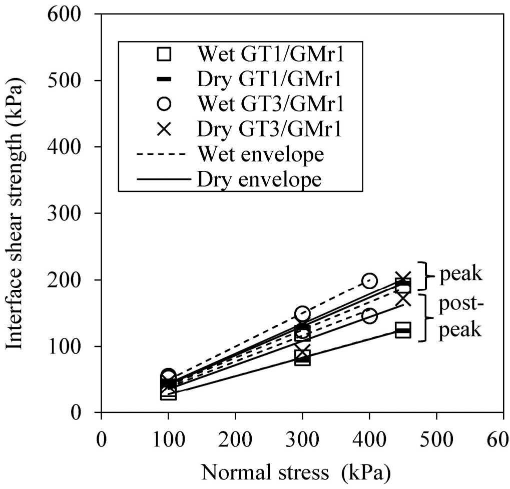

Fig. 2. Geotextile/geomembrane interface shear strength in wet and dry conditions.

Fig. 3 presents the typical interface shear strength behavior for nonwoven geotextile/textured geomembrane interfaces. The shear strength−shear displacement curves in Fig. 3a show strain softening behavior, i.e. the interface shear strength decreases with increasing shear displacement (Byrne, 1994; Stark et al., 1996; Jones and Dixon, 1998). The higher the normal stress, the higher the strain softening behavior. This phenomenon is observed in rock joints but contrary to geosynthetic interfaces, the higher the normal stress in this case, the lower the strain softening behavior. Based on this fact, Bacas et al. (2011) proposed a new shear constitutive model for this type of interface.

In this study, approximately 60% of the tests reveal nonlinear failure envelopes whereas 40% are linear envelopes. Fig. 3b shows nonlinear peak and post-peak failure envelopes (continuous lines). However, the straight envelopes, passing through the origin (dashed lines) with peak and post-peak friction angles of 24° and 12°, respectively, also show a good fit (R^2>0.9).

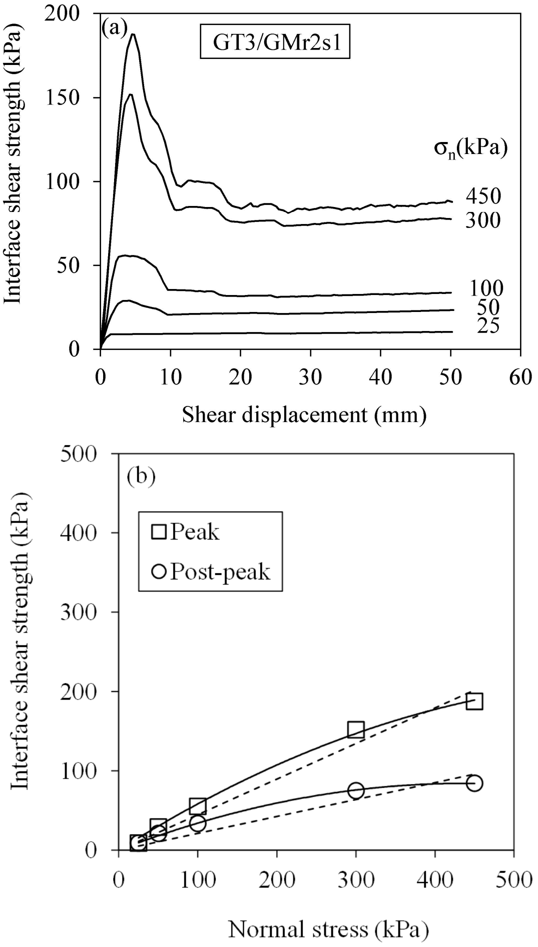

Fig. 3. Typical interface shear strength behavior for nonwoven geotextile/textured geomembrane interfaces. (a) Shear strength vs. shear displacement curves, and (b) Peak and post-peak failure envelopes.

In line with Giroud et al. (1990), Koutsourais et al. (1991), Stark et al. (1996), Hebeler et al. (2005) and McCartney et al. (2009), the interaction mechanisms during the shear tests on nonwoven geotextile/textured geomembrane interfaces show the following behaviors:

(1) At low normal stress (<50 kPa), the interaction between nonwoven geotextiles and the textured geomembranes consists of two mechanisms: (i) one is the interlocking (hook and loop) between the superficial filaments of the geotextile and the asperities of the geomembrane, (ii) the other is the friction between the materials. Both take place on a superficial level.
(2) As the normal stress increases (>50 kPa), the geotextile is compressed and the asperities are introduced into the geotextile matrix, which is called interbedding factor. Thus, the friction and interlocking interactions take place on a matrix level.

Fig. 4 illustrates how the peak interface shear strength is reached for a small shear displacement (peak displacement), during which the friction angle is mobilized first and then the hook and loop interact, causing the shear strength to reach its peak. After the peak, the hook and loop mechanism degrades since the filaments are pulled out, torn and untangled from the geotextile until the residual interface shear strength is reached.

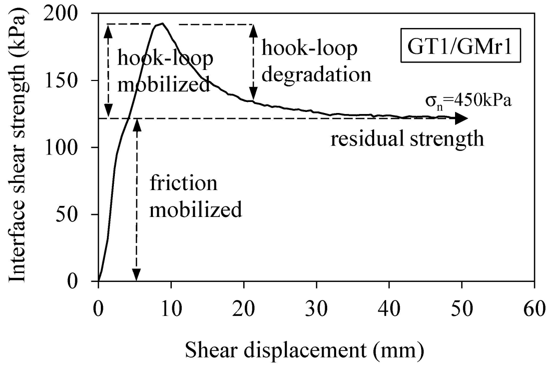

Fig. 4. Illustration of the decomposition of strain softening behavior.

Bacas et al. (2011) developed an interface shear model based on rock joint theories, quantifying the interbedding and the interlocking (hook and loop) factors, which depend mainly on the type of geotextile and the asperities of the geomembrane. Their respective ranges are 1–3 for the interbedding factor and 2–8 for the interlocking factor. The higher the asperity height, the higher the interlocking factor. Besides, the larger the hollows of the geotextile, the higher the interbedding factor. An example for such a geotextile would be one made of staple fibers.

5. Influence of roughness characteristics of the geomembranes on interface shear strength

5.1. Effect of roughness patterns

The differences between the various roughness patterns are analyzed through the interface shear strength vs. shear displacement curves of the nonwoven needle-punched geotextile, GT1. Fig. 5a presents the GT1/GMr1, GT1/GMr2s1 and GT1/GMr3 results. GMr1 has a rough, irregular texturing while GMr2s1 and GMr3 have regular asperities, as shown in Fig. 6, which presents microscope images of roughness. Interface shear strength presents similar values at normal stress lower than 50 kPa and depends neither on the roughness pattern nor on the asperity height. At normal stress higher than 50 kPa, regular texturing normally shows larger interface shear strength and strain softening behavior than irregular texturing. The downward stepping post-peak curves of GMr3 and GMr2s1 with their successive peaks (mini-peaks) are caused by the deterioration of the geotextile fiber weft, as can be observed at normal stress of 300 kPa. The separation between the mini-peaks matches the separation between the asperities. GMr3 and GMr2s1 have asperities spaced at 6 mm and 9 mm in staggered rows, respectively. Therefore, the GMr3 presents larger peak and post-peak interface shear strengths than GMr2s1. This means that the closer the asperities are, the better the result achieves but without becoming too close, because the surface could become uniform. One has to bear in mind, however, that until 100 kPa, the shear results of GMr3 and GMr2s1 show similar values.

Fig. 5b illustrates the results of three different geomembranes with different roughness patterns and different asperity heights less than 1 mm. GMr2s2 has regular asperities spaced at 4 mm, and GMr1 and GMr4 have rough irregular texturing, however GMr1 is rougher than GMr4 (Fig. 6). The curves at normal stress of 50 kPa are similar, but at normal stress higher than 50 kPa, the differences between roughness patterns affect the interface shear strength. GMr1 and GMr2s2 show an increased frictional performance compared with GMr4. The post-peak curves are uniform without any successive steps, even though the GMr2s2 has regular asperities, but these are too close.

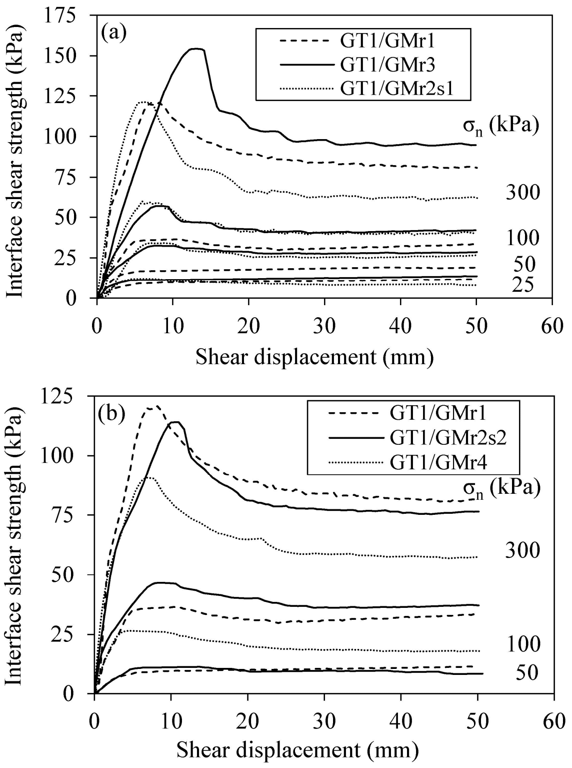

Fig. 5. Comparison of different roughness patterns: (a) regular (GMr3, GMr2s1) and irregular (GMr1) texturing, (b) irregular texturing with asperity height less than 1 mm.

5.2. Effect of asperity height

Fig. 7 presents the interface friction angles vs. asperity heights. The following important aspects are observed:

1. The smaller values of interface friction angle belong to the smooth geomembrane (GMs). Shear strength is purely frictional; hence the geotextile/GMs interfaces present similar peak and post-peak friction angles.
2. The higher the geomembrane roughness, the higher the peak interface shear strength (Ivy, 2003; McCartney et al., 2005). Therefore, GMr2s1 and GMr3 show the greatest peak values while GMr4 presents the smallest peak friction angles.
3. The geomembranes with an asperity height larger than 1 mm present greater post-peak interface strength loss due to their high capacity of damaging the geotextile fiber wefts.
4. The post-peak values do not show a clear trend related to the size of the asperity, but they do show dependency on the type of geotextile (McCartney et al., 2005).

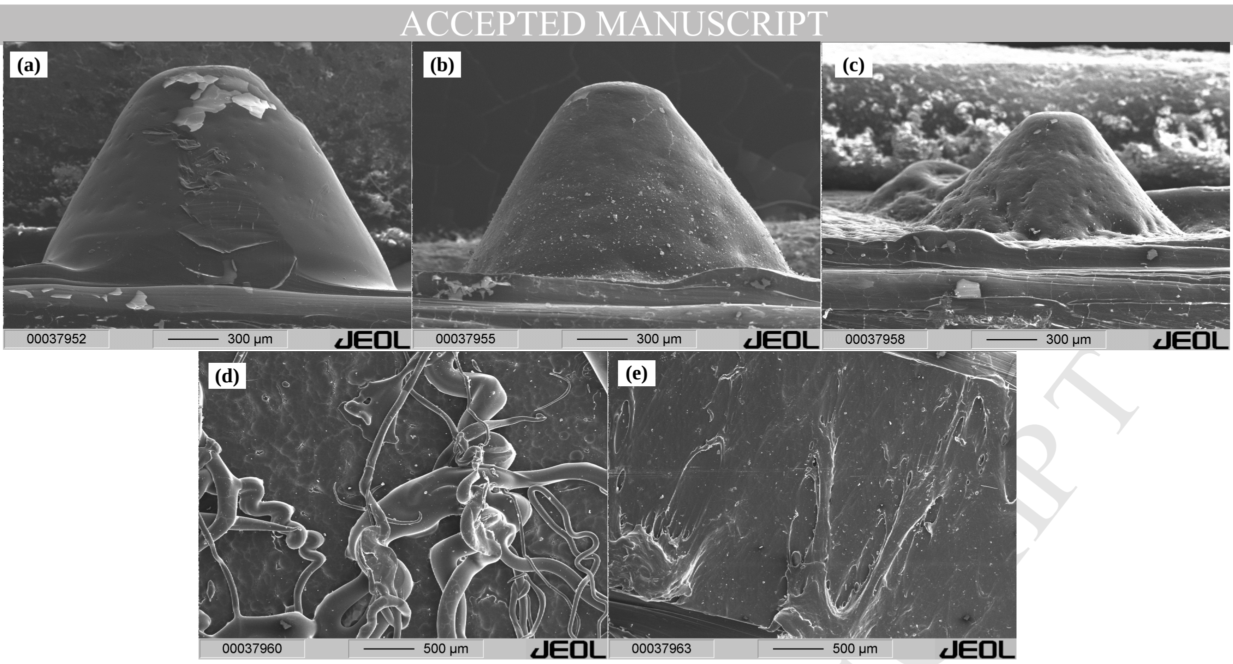

Fig. 6. Scanning electron microscope (SEM) images of roughness of geomembrane. Asperity average height: (a) GMr3: ~1.3 mm, (b) GMr2s1: ~1.2 mm, (c) GMr2s2: ~0.8 mm, (d) GMr1: ~0.5 mm, (e) GMr4: ~0.25 mm.

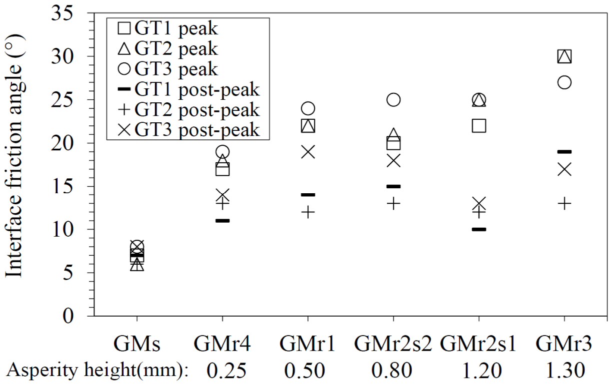

Fig. 7. Friction angles of geotextile/geomembrane interfaces tested in wet conditions.

6. Influence of fiber characteristics of the geotextile on interface shear strength

6.1. Effect of fiber length

The influence of the geotextile fibers' length on the interface shear strength is observed through comparing the nonwoven needle-punched geotextiles GT1 and GT2 in Fig. 8. They are made of monofilament and staple fibers, respectively, as shown in Fig. 9a and b, which are microscope plots of the fibers. At normal stress lower than 100 kPa, GT1 presents larger peak values than GT2. This is because the length of the fibers greatly affects the interface shear strength at low normal stress, as can be observed in Fig. 10a, which depicts the interface shear strength vs. shear displacement curves at normal stress of 50 kPa. GT2 presents a smaller interface shear strength, because on a superficial level, the staple fibers do not develop the interlocking mechanism as much as the monofilament of GT1 does. However, at normal stress higher than 100 kPa, the peak values are closer for both materials (Fig. 8). The lower post-peak values belong to the GT2 because its staple fibers are easier to damage than the monofilaments weft, which are more intertwined.

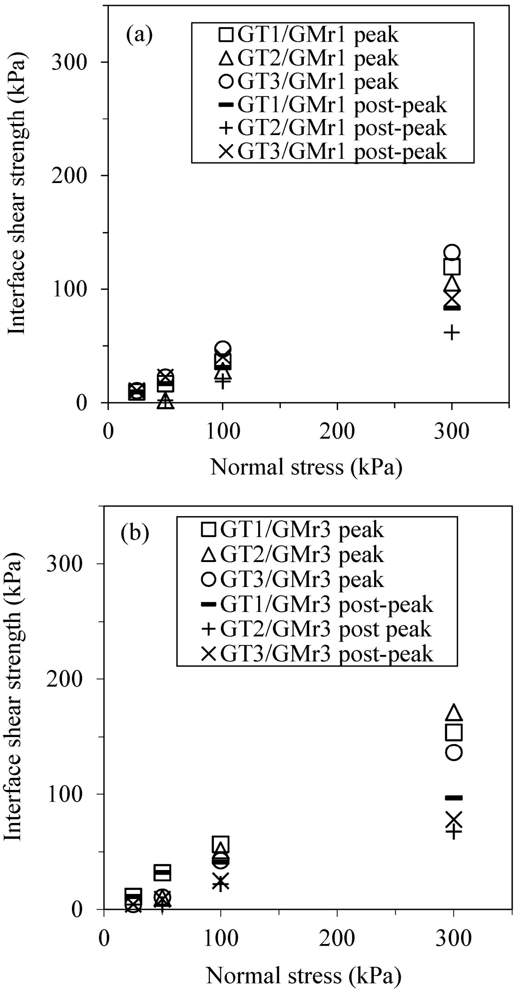

Fig. 8. Comparison of interface shear strength between 3 nonwoven geotextiles. (a) Geotextile/GMr1, and (b) Geotextile/GMr3.

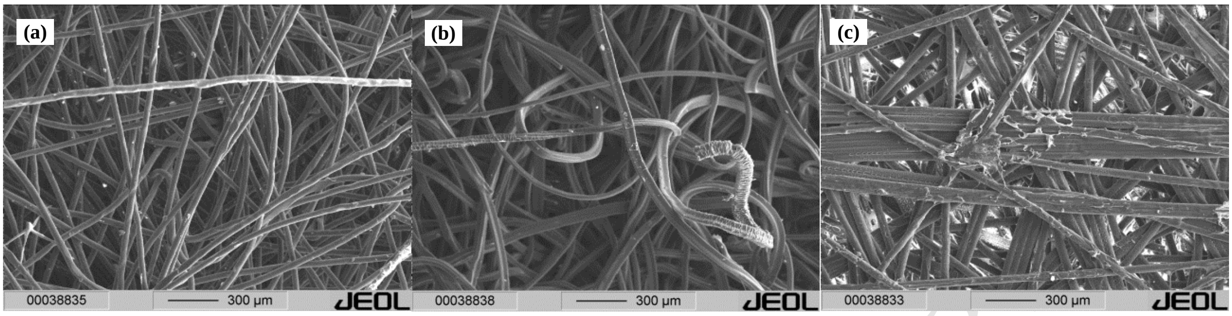

Fig. 9. SEM images of nonwoven geotextiles. (a) GT1: needle-punched monofilament, (b) GT2: needle-punched staple fibers, (c) GT3: thermally bonded monofilament.

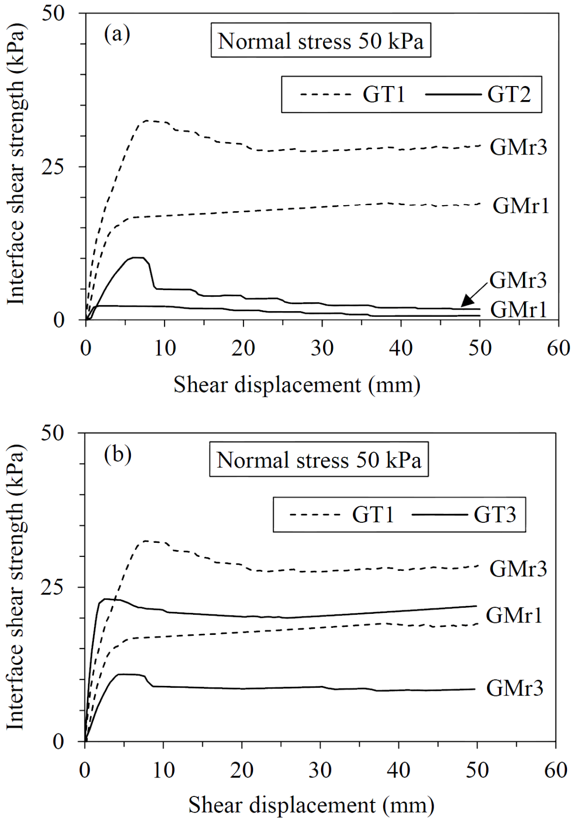

Fig. 10. Comparison of interface shear strength at low normal stress for (a) needle-punched geotextile (GT1, GT2)/GMr, (b) needle-punched geotextile (GT1)/GMr and thermally bonded geotextile (GT3)/GMr.

6.2. Effect of geotextile manufacture

The influence of the manufacture of the geotextiles can be observed through comparing the nonwoven monofilament geotextiles GT1 and GT3. The former is a needle-punched fabric and the latter is a thermally bonded one. Fig. 9a and c prove that GT1 has looser filaments and larger hollows than GT3. The latter shows a higher interlocking leading to a higher interface shear strength, as shown in Figs. 7 and 8a. An exception to this is presented in Fig. 8b, where the GT3/GMr3 interface presents the lowest interface shear strength. The asperities cannot penetrate the geotextile matrix deeply enough because of the smaller hollows. Moreover, the regular texturing creates linear tracks through the geotextile which acts like a plow, stretching the superficial filaments, as can be observed in Fig. 11a which shows the samples after testing. Fig. 11b indicates that the interaction between GMr1 and GT3 leads to higher interlocking (hook and loop) due to the greater entanglement between the filaments and the irregular roughness. This behavior is also observed at low normal stress (see Fig. 10b).

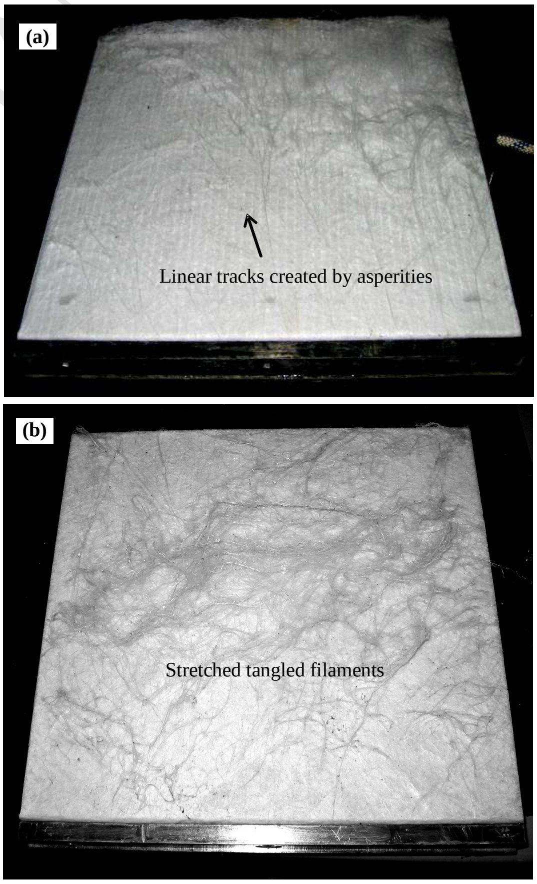

Fig. 11. Thermally bonded geotextile after testing at normal stress of 300 kPa. (a) GT3/GMr3, and (b) GT3/GMr1.

The post-peak interface shear strengths mainly depend on the type of geotextile. Usually, GT3 presents the largest post-peak values, because thermally bonded monofilaments are stretched and very tangled during the shear, causing a higher resistance as the geomembrane slides over the geotextile. However, the needle-punched monofilaments of the GT1 are stretched and brushed in shear direction, facilitating the geomembrane to slide over the geotextile's surface. Finally, GT2 normally presents the lowest post-peak values because its staple fibers are stretched and brushed most easily.

The conclusion from these analyses is that the manufacturing process of the geotextile influences both the peak and the post-peak interface shear strengths. If the roughness of the geomembrane is irregular and dense, we recommend using thermally bonded monofilaments, because the interlocking mechanism has a major influence on interface shear strength. If, however, the roughness is regular and uniform, we rather recommend using needle-punched filaments, especially for high normal stress levels, where the interbedding factor has higher influence on the interlocking mechanism and thereby on the interface shear strength. Finally, for cover systems of the landfills subject to low ranges of normal stresses (<100 kPa), it is recommended using monofilament rather than staple fibers, because the former mobilizes the interlocking mechanism at lower normal stresses better than the latter.

7. Conclusions

The study of large direct shear tests conducted on geotextile/geomembrane leads to the following main conclusions:

(1) The interface interaction mechanisms depend on normal stress. At low normal stress (<50 kPa), interlocking and friction develop at a superficial level. At high normal stress (>50 kPa), interlocking and friction develop at a matrix level.
(2) If the roughness of the geomembrane is irregular and dense, it is recommended using the nonwoven geotextile made of monofilaments, because it develops larger interlocking mechanism causing the shear strength to increase.
(3) If the roughness of the geomembrane is regular and evenly spread, it is recommended using the nonwoven geotextile with needle-punched filaments, especially for high normal stresses (≥100 kPa), where the interbedding factor has larger influence on the interlocking mechanism and thus on the shear strength.
(4) For cover systems of the landfills subject to low normal stresses (<100 kPa), it is recommended using monofilaments rather than staple fibers, since the former mobilize the interlocking mechanism at lower normal stresses.
(5) For regular textured geomembranes, the space between the asperities is an important factor. The closer these asperities are, the better the result achieves. Nevertheless, they should not be too close because the surface could become uniform, thereby decreasing the interlocking mechanism.

Conflict of interest

The authors confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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