Influence of the displacement rate on direct shear behaviour of geotextile interfaces

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ABSTRACT: The development of friction forces between two geotextiles is present in some engineering applications, playing a key-role on the stability of some of them. Coastal structures constructed with geotextile encapsulated-sand systems are a good example of an application where friction forces between geotextiles are key to stability. So are, landfills, as they can handle multiple geotextiles overlapped to create a heavier cushion layer. Hence, assessing the friction development between two geotextiles is a scope of great interest for which design guidance or formulae are yet much needed and the available experimental data is scarce. This paper is part of an ongoing research on sand-filled geosystems for coastal protection at the University of Porto and presents selected results on a laboratory study, carried out using a large-scale direct shear device, to examine the shear behaviour of geotextile's interfaces under different shear displacement rates. Tests were conducted under monotonic loading conditions for shear displacement rates ranging from 1mm/min to 12 mm/min. Two different interfaces using a woven and a non-woven geotextile were investigated. The results indicated that the shear displacement rate has a significant influence on the interface shear strength, so that an increase in the displacement rate induces the decrease of the shear strength.

1 INTRODUCTION

The development of friction between two geosynthetics is found to be important for structures such as geotextile encapsulated-sand systems used for shore protection, temporary structures to prevent flooding, and landfills handling multiple geotextiles overlapped. In some of those applications, the knowledge of the appropriate geosynthetic-geosynthetic friction angle is required for the analysis of stability, being its quantification necessary.

A considerable amount of data, much of which derived from the research area of landfills, has been published on the friction behavior on an interface between a geotextile and a geomembrane, by means of direct shear tests (e.g. Jones & Dixon 1998, Wasti & Özdüzgün 2001 and Lopes 2013).

However, references on the study of the shear behavior between two geotextiles are scarce, existing only a few references in the literature and selected data provided by geotextile manufacturers.

In his study, Recio (2008) pointed out some earlier references regarding the investigation of friction between two geotextiles, namely Grett (1984), Kim *et al*. (2004) and Naue (2004), which performed direct shear tests on geotextile interfaces using shear devices with dimensions 0.30m × 0.30m. Grett (1984), systematically tested woven and non-woven geotextiles referring friction angles from 16˚ to 18˚ for a woven geotextile, 20˚ to 26˚ for mechanical-nonwoven geotextiles and 23˚ to 30˚ for thermal-nonwoven geotextiles. Kim *et al*. (2004), tested a non-woven geotextile, and reported a friction angle of 35˚, although very poor information was given about the characteristics of the materials and test conditions. Naue (2004) reported a friction angle between 20˚ and 26˚ for a non-woven geotextile.

Nielsen & Mostyn (2011) reported for a non-woven geotextile, friction angles of 20˚ and 18˚, estimated using shear boxes of dimensions 0.1m × 0.1m and 0.5m × 0.5m, respectively

The application of geotextiles in coastal protection structures, as geotextile encapsulated-sand systems, is becoming widespread owing to some recognized advantages. The quantification of the friction contribution for the stability of these systems is presently a scope of great research interest. According to Dassanayake & Oumeraci (2012), the friction development in these structures mainly depends on: friction characteristics of the geotextile material; contact area between elements; overlapping length; sand fill ratio; and type of fill material. The same authors reported friction angles of 13.3˚ and 22.6˚, estimated by means of underwater direct shear tests, for a woven and a non-woven geotextile, respectively. These friction angles were found to be roughly proportional to the pullout resistance of the geotextile sand containers, GSCs, built with each material. Direct shear tests results seem to be an adequate way to quantify the friction resistance on the interface between GSCs, focusing on the first and last items above mentioned, that is the friction characteristics of the geotextile material and the type of fill material.

As better the prototype conditions are represented in the laboratory tests, as higher is the reliability of the estimate. Hence, accurate testing conditions, with respect to confinement pressure and shear displacement rate between the geotextile surfaces, are key to the achieved results.

Geotextile encapsulated-sand systems when exposed to wave attack, experience a wide range, in magnitude and frequency, of externally imposed forces. The friction forces developed by small or large sliding between sand-filled elements in prototype is better reproduced by means of direct shear tests with low and high displacement rates, respectively.

The present experimental study gives a contribution to assess the influence of the direct shear displacement rate on shear strength estimation, showing the interest in consider a specific displacement rate (or a range of displacement rates) in order to better simulate prototype conditions in laboratory. To the knowledge of the authors, this investigation is the first reporting results of geotextile-geotextile direct shear test series, and thus making contributes to the knowledge available on the topic.

2 EXPERIMENTAL PROGRAM

2.1 Test apparatus

The tests were conducted in a direct shear apparatus developed at the Geosynthetics Laboratory of the Faculty of Engineering of the University of Porto (FEUP), according to the recommendations of the European standard, prEN ISO 12957-1 (2001), and the American standard, ASTM D 5321-92 (1992). This direct shear device comprises a upper box, fixed in the horizontal direction (of dimensions 0.3m × 0.60m in plan and 0.15m height), and a lower box (of dimensions 0.34m × 0.60m in plan and 0.10m deep), rigidly coupled to a mobile platform, which allows the shear displacement (Fig. 1). In this study only the upper box was filled with soil being inserted a rigid base in the lower box. This direct shear device, developed with the aim to be the more versatile as possible, is able to perform monotonic and cyclic direct shear tests. The device also permits carrying out direct shear tests on soil-geosynthetic interfaces and geosynthetic-geosynthetic interfaces. A detailed description of the equipment is available from Vieira *et al*. (2013).

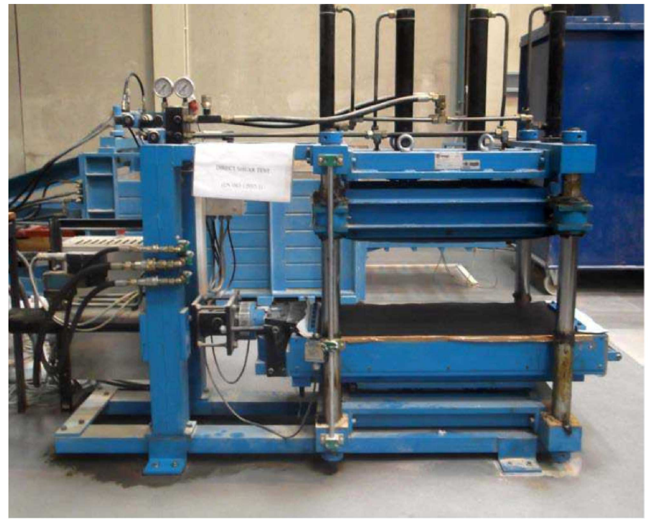

Figure 1. General view of the direct shear device at Geosynthetics Laboratory of FEUP.

2.2 *Materials and general test setup*

The choice of the materials used in the present laboratory investigation, namely the geotextiles and the soil, is related to the research project of which this study is part of. Further information about the rationale on the selection of these materials and the context of the research can be found in das Neves (2011).

Two geotextiles were used to create the target shear interfaces, namely a needle-punched non-woven geotextile and a woven geotextile. The interfaces were designated as: Interface G1 – interface between two samples of a non-woven geotextile; and Interface G2 – interface between two samples of a woven geotextile.

The the most relevant geotextile properties for the current study are presented in Table 1.

Table 1. Properties of the geotextiles used in the interfaces G1 and G2.

Property	Unit	G1	G2
Raw material	-	Polypropylene white	Polyethylene black
Mass per unit area	g/m^2	300	300
Thickness	mm	1.6	-
Tensile strength	kN/m		
MD*		13	40
CD*		22	20
Elongation at nominal strength	%		
MD*		50	20
CD*		30	20
Characteristic opening size	µm	70	230
Water permeability	l/m^2s	40	65

* MD: machine direction, CD: cross direction.

A picture showing the geotextile surfaces is given in Figure 2.

The soil used in the tests is a silicated sand (referenced as SP55) with median grain size diameter of 453 μm and a density of $2.55g/cm^3$.

Regarding the specimens preparation, the geotextiles were cut into samples of 0.90m long and 0.40m wide. The non-woven samples were prepared to be tested only in fabric direction, while the woven ones will be tested in the direction that the shear occurs in the models and prototypes, more frequently. The woven geotextile specimens were prepared having non-woven geotextile reinforcements on the grips to avoid material shredding during the tests. New specimens were used in every test.

For the test setup, the geotextile specimens were fixed on the lower and on the upper boxes, after being properly stretched and positioned (Fig. 3). Then, the upper box was lowered leaving 1mm spacing between boxes.

In every test, the upper box was filled with a sand layer of 5cm thick. Preliminary tests to the interface G2 revealed sediment losses of the smallest sand particles, thus wet sand was used in these tests to minimize it. For the interface G1, all tests were conducted with the upper box filled with dry sand. Soil compaction was achieved using a pestle, which is the available method for the device used. For the tests with dry sand, 14.9kg of sand were compacted until the layer reached thickness of 5cm; whereas for the wet ones, the soil was prepared using a mixture of 14.2kg of sand to 1L of water, again compacted a 5cm thick layer The horizontal leveling of the sand layer before starting the application of the normal stress is granted by lowering the loading plate.

Measurements of the vertical displacements of the loading plate were taken with a Linear Variable Differential Transformer, LVDT, allowing the evaluation of the volumetric deformations of sand placed inside the upper box.

Figure 4 shows the positioning of the LVDT transducer in the center of the loading plate.

Testing is comprised of two stages: a primary stage of loading and a second stage of shear displacement. Preliminary one-hour duration tests revealed that in few minutes the vertical settlements tend to an asymptotic behavior, which led to the definition of a stage of 15-minutes loading. After that the shear movement starts, with a pre-defined displacement rate, until it reaches a maximum displacement of 60mm.

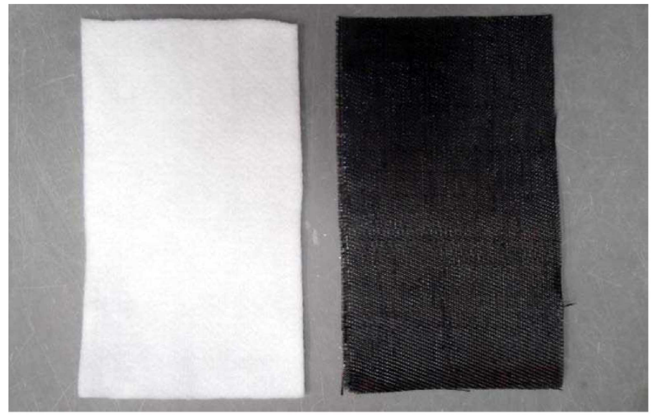

Figure 2. Surfaces of the non-woven geotextile, G1, (left), and the woven geotextile, G2, (rigth).

Figure 3. Woven geotextile samples positioned in the direct shear device, with reinforcements on the grips.

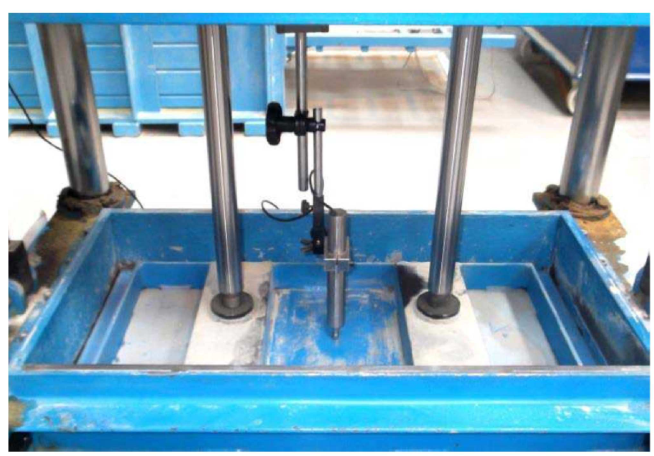

Figure 4. Positioning of the LVDT transducer in the center of the loading plate.

2.3 *Schedule of experiments*

The tests were conducted for normal stresses of 25, 50 and 75kPa. Again the rationale behind these choices are based on the confining pressure conditions expected in the physical models to be performed within the research project of which this paper is part of, with due consideration of model scale relations and the shearing area of the used testing device. Four shear displacement rates were adopted, namely 1, 3, 6 and 12mm/min.

Three tests were performed at each test condition to increase feasibility of results.

A total of 72 large scale direct shear tests were performed, matching the possible combinations among normal stress and shear displacement.

3 EXPERIMENTAL RESULTS

The results of the direct shear tests are analyzed in this section in terms of stress-displacement curves and Mohr-Coulomb failure envelopes.

3.1 *Stress-displacement curves*

For the two geotextile interfaces tested, G1 (non-woven geotextile) and G2 (woven geotextile), the stress-displacement curves show a shear behaviour comprising a pre-peak and a post peak phases. Figures 5-6 present plots of the shear stress versus shear displacement curves, for the interfaces G1 and G2, respectively. Each curve represents the average of the three tests performed at each test condition.

As expected, the results show that the shear strength increases with applied normal stress. Higher peak shear stresses were achieved with the interface between woven geotextiles, which might be explained by its higher surface roughness when compared to the smooth non-woven one.

Generally, for both geotextile interfaces, the shear displacement required to mobilize the peak shear strength increases with the increase of normal stress and decreases with the shear displacement rate. This effect is more visible on the interface G2. In general, the peak shear stress is reached for a small shear displacement in the interface G1 (usually less than 4.5mm) and at a displacement between 5 and 20mm in the interface G2.

During the peak and post-peak phases the interface G1 evidences a shear strength decrease that is-more noticeable than in the interface G2, which can keep higher shear strengths for longer. For the lowest shear displacement rate (1mm/min), the post-peak phase shows a stabilization in the shear strength around a residual value, which occurred predominantly after a 3cm of displacement in the interface G1, and for higher displacement values in the interface G2.

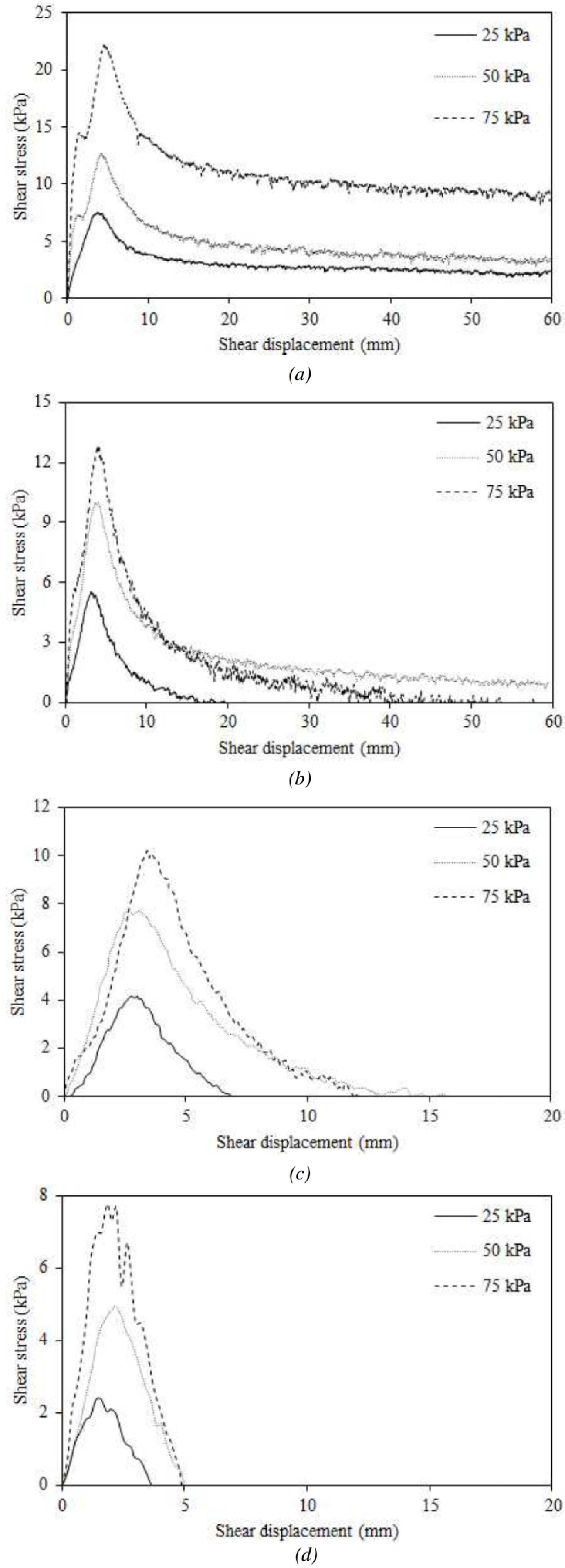

Figure 5. Stress-Displacement curves obtained for the interface G1 with shear displacement rate of: *(a)* 1 mm/min; *(b)* 3 mm/min; *(c)* 6 mm/min and *(d)* 12 mm/min

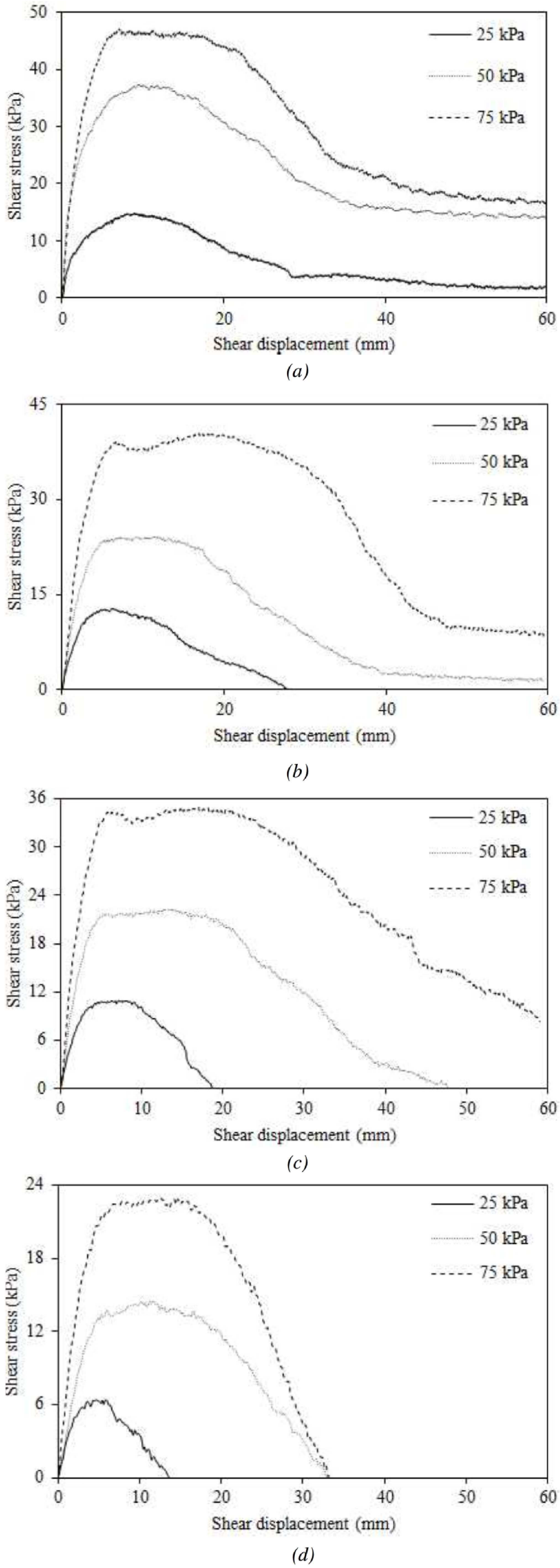

Figure 6. Stress-Displacement curves obtained for the interface G2 with shear displacement rate of: *(a)* 1 mm/min; *(b)* 3 mm/min; *(c)* 6 mm/min and *(d)* 12 mm/min.

For higher displacement rates and particularly, under lower vertical stresses, the post-peak phase was characterized by very small shear strengths, registered by the load cell as null or negative values, for which a shear strength stabilization was not observed.

The post-peak strength loss exhibited by the interface G2 is mainly attributed to the tearing of filaments of the geotextile during shear, as well as, by the comb of the filaments parallel to the shear direction, both aspects were quite evident in these samples after testing. The strain-softening behavior observed in the non-woven geotextile samples were attributed to the separation and orientation of the geotextile fibers in the shear direction, visible after testing. These behaviours were more obvious for higher normal stresses.

Regarding the evaluation of the variability of results obtained within repeated test series, measures of statistical dispersion were calculated, namely average, standard deviation and coefficient of variation. Table 2 presents a summary of the computed coefficients of variation of the peak shear stress, considering the three tests performed at each test condition. In general, the coefficients of variation are small in the tests with higher shear strengths, namely for the test conditions characterized by lower displacement rates and higher normal loads. For the mentioned test conditions a satisfactory degree of repeatability was found. The tests carried out under a low normal load, 25kPa, have showed a significant dispersion in results, and thus interpretation must be carefully done. The higher standard deviations found for the peak shear stress were 1kPa for the interface G1 and 2.3kPa for the interface G2. After the peak shear strength variations become larger evidencing coefficients of variation of 20%, on average, for the residual shear strength (displacement rate of 1 mm/min). In the scope of the investigation, residual shear strength was defined as the average of the records during the last 10cm of shear displacement.

Table 2. Coefficients of variation obtained for all test conditions (%).

Setting			Shear displacement mm/min			
			1	**3**	**6**	**12**
		25	8.6	10.8	11.3	22.5
G1	Normal	**50**	0.9	4.7	8.3	8.1
	Stress	**75**	4.3	3.3	6.2	7
		25	4.3	9.7	20.6	7.9
G2	(kPa)	**50**	2.9	3.1	5.2	6
		75	0.8	1.7	3	1.5

Figures 7-8 show the influence of the shear displacement rate on the peak shear strength of the interfaces G1 and G2, respectively, within the same confining pressure conditions.

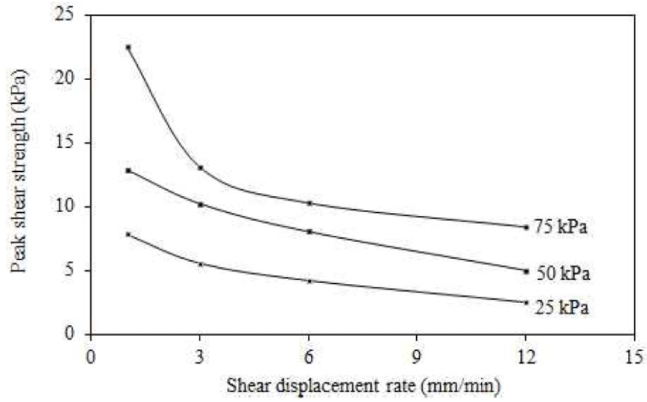

Figure 7. Influence of the shear displacement rate on peak shear strength of the interface G1.

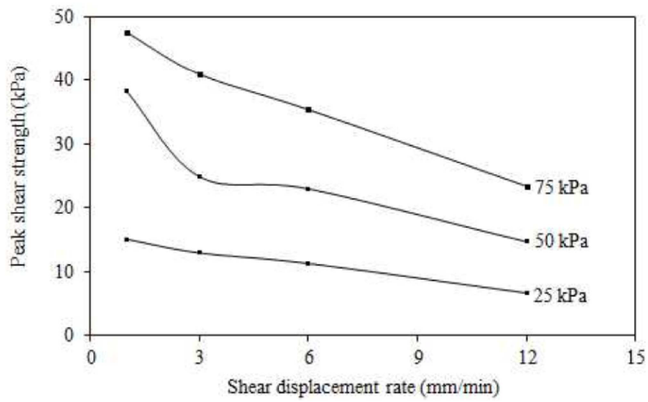

Figure 8. Influence of the shear displacement rate on peak shear strength of the interface G2.

An increase in the displacement rate induces a decrease on the peak shear strength. This effect is more noticeable for higher confining pressures on both interfaces, and shows an asymptotic behaviour in interface G1. The vertical displacements of the loading plate show the volumetric deformations of the sand inside the upper box, during the shearing (Fig.9).

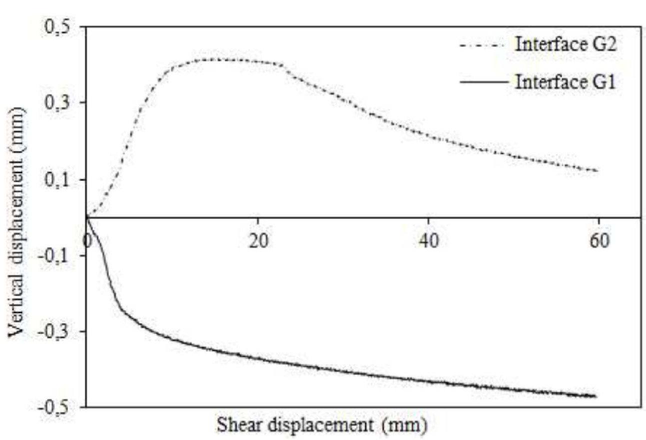

Figure 9. Vertical displacement of the loading plate *versus* shear displacement (example for test conditions with normal stress of 50 kPa and displacement rate of 3 mm/min).

In general, small vertical displacements, not exceeding 1mm, occurred for the majority of the performed tests.

The dry sand used in the tests to the interface G1 exhibited a contractile behavior for the overall tests, whereas, the wet sand used in the tests to the interface G2 showed a dilatant behaviour. For the overall testing, the influence of the normal stress and the shear displacement rate on the vertical displacements was not significant.

3.2 *Failure envelopes and friction angles*

The friction parameters are defined in the same way as the soil mechanical parameters according to the Mohr-Coulomb failure criterion expressed as:

$$\tau = \sigma \tan\phi + a \qquad (1)$$

where τ is the shear strength, σ is the normal stress, a is the intercept of the failure envelope with the vertical axis, and ϕ is the slope of the failure envelope. This equation can be written for peak and residual shear strength conditions. The quantity a is usually called the adhesion for geosynthetic-geosynthetic interface tests or cohesion for tests involving soils, and the parameter ϕ is called the friction angle.

Figures 10-11 present the peak failure envelopes and the residual failure envelopes (for the displacement rate of 1mm/min), obtained by fitting straight lines to the data points of τ and σ, for the target interfaces G1 and G2, respectively. The peak failure envelopes, fitted by linear regression, have linear correlation factors, R^2, ranging from 0.936 to 0.989. The lowest values for the factor R^2, may suggest a nonlinear behaviour, especially for residual strength conditions where the correlation factors fell to 0.728 in the interface G1 and 0.826 in the interface G2. Carrying out tests under more normal load conditions would be important to better clarify this possible nonlinear behaviour.

Although, a linear regression is generally considered to determine the failure envelopes, attention must be paid to the observed nonlinearity.

Giroud *et al.* (1993) proposed a hyperbolic expression to represent the nonlinearity of the relation between the shear strength and the normal load, consistent with interface shear strength values obtained in laboratory direct shear tests. According to the same authors, the use of a linear relationship may lead to significant errors, especially in cases where normal stresses are small, such as geosynthetic liner systems covered with thin layers of soil, or cases where the normal stresses vary considerably along the potential failure surface, such as geosynthetic liner systems covered with piles of waste or ore.

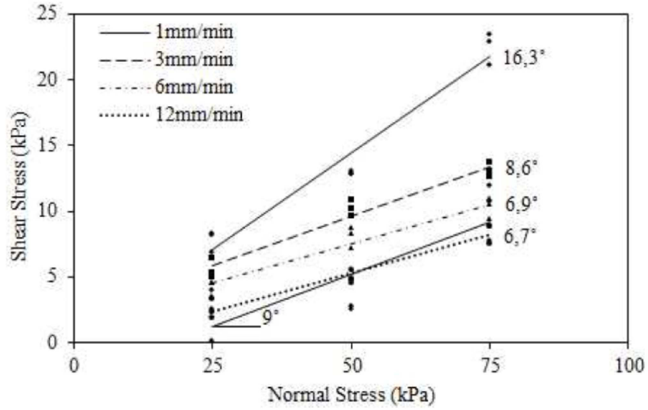

Figure 10. Failure envelopes for the Interface G1.

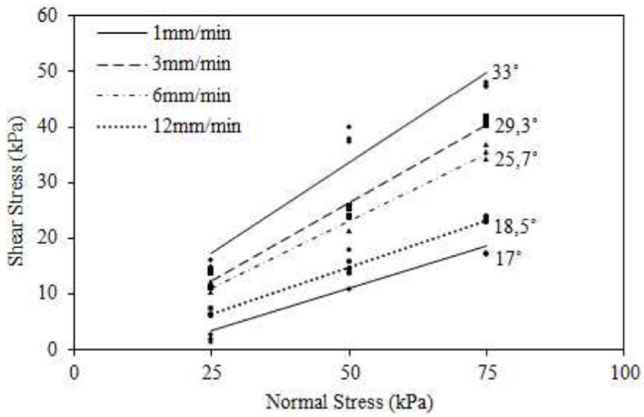

Figure 11. Failure envelopes for the Interface G2.

Focusing on the peak and residual failure envelopes, defined for the shear displacement rate of 1mm/min, the strength loss during the post-peak phase corresponds to a reduction in the friction angle of approximately 45% in the interface G1 and 53% in the interface G2. As observed, the friction angle decrease with an increase in the shear displacement rate. Again, an asymptotic tendency is verified for the interface G1 (Fig. 12).

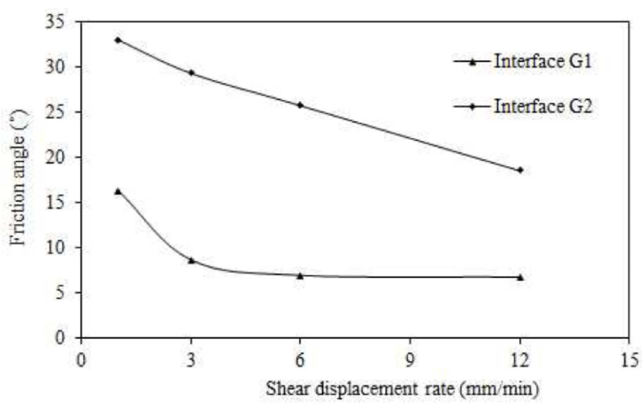

Figure 12. Influence of shear displacement rate on the friction angle for both interfaces.

As mentioned by Thiel (2009), the values of ϕ and "*a*" should be considered nothing more than mathematical parameters to describe the shear strength *versus* normal stress behaviour, over the normal-load range that the tests were conducted, so that friction and adhesion should not be seen as real material properties. Even though the friction angle refers to the behaviour of the interface within the limits of the tested normal stresses, the parameter "a" fells out of this range, once it means "the shearing resistance between two adjacent materials under zero normal stress" (ASTM D 5321), which is generally of no use.

For the already mentioned reasons, extrapolations beyond the limits of the tested normal stresses must be avoided, once safety especially at low normal stresses present during construction, can be comprised. Thiel (2009) states that the safest way to accomplish extrapolations beyond the limits of the tested normal stresses is going from the low end of the Mohr-Coulomb envelope and extrapolating backward, drawing a straight line back to origin and drawing a straight line horizontally forward from the high end of the envelope. For these reasons none consideration was made about the parameter "a" obtained for these tests.

4 CONCLUSIONS

This paper described the direct shear behaviour of two different geotextile interfaces, namely one interface between two samples of a non-woven geotextile and another one between two samples of a woven geotextile. The shear displacement rate was varied along the test series to assess its influence on the interface shear strength. The following conclusions are based on the data and the discussion given along the paper.

- The interface composed by the woven geotextile presented higher shear strength comparatively to the non-woven one, which was attributed to the higher roughness of its surface. Thus, the geotextiles' surface texture can provide a substantial increase in the interface shear strength.
- The shear strength increased with an increase in the applied normal load. For the tests carried out under higher normal loads, damage of the woven geotextile texture occurred.
- For lower normal loads and higher shear displacement rates, both geotextile interfaces yielded very small shear strength values, to such an extent that they were registered by the load cell as null or negative. In these cases there was no visible stabilization of the shear strength.
- Each test condition was repeated three times and the variation of results appeared to be highly in-

fluenced by the magnitude of the determined shear strengths. The higher the shear strength, the lower the variation of results.

– Geotextile-geotextile interface failure envelopes can be non-linear especially for low displacement rates. So, the evaluation of the interface shear strength for design proposes requires caution for this type of interface and extrapolations beyond the limits of the tested normal stresses must be avoided. It is recommended to use the entire failure envelope (or a friction angle that corresponds to the appropriate normal stress) in the stability analysis.

– The shear displacement rate influences the achieved interface shear strength. An increase in the displacement rate leads to the estimation of lower shear strengths and lower friction angles. For the interface between two non-woven geotextiles this tendency showed an asymptotic behaviour, however, for the interface between two woven geotextiles the tendency seem to not stabilize within the range of tested displacement rates. Thus, for this type of interface, considerations on the choice of the shear displacement rate must be done before testing.

ACKNOWLEDGEMENTS

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