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SOIL-GEOSYNTHETIC INTERFACE STRENGTH PROPERTIES FROM INCLINED PLANE AND DIRECT SHEAR TESTS – A COMPARATIVE ANALYSIS

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ABSTRACT

Direct shear tests are typically used to estimate soil-geosynthetic interface shear strength under relatively high normal stress values. For low values of normal stress, mechanical difficulties related to the control of normal stress may affect the accuracy of results. The inclined plane test is an alternative method to evaluate interface properties under low confining pressures. This paper establishes a comparison between the results from inclined plane and direct shear tests carried out to characterise the interfaces between two geosynthetics and a granite residual soil under dry and moist conditions. Test results show that soil-geosynthetic interface shear strength parameters estimated from direct shear tests were consistently higher than those evaluated by inclined plane tests. Despite the differences in the normal stresses and kinematics associated with the distinct methods, it was possible to describe, with reasonable accuracy, the soil-geosynthetic interface shear strength over the normal stress range of 5-150 kPa, using a Mohr-Coulomb shear strength envelope.

1. INTRODUCTION

Interaction between soils and geosynthetics is of the utmost importance for design and stability analysis of geosynthetic-reinforced soil structures. This is also the case when geosynthetics are applied in some environmental protection systems. The design and adequate performance of these structures throughout the design working life requires proper assessment of the interface shear strength properties between soils and geosynthetics or between different geosynthetics. Direct shear tests are commonly used to estimate soil-geosynthetic interface strength properties under relatively high normal stress values (usually greater than 50 kPa). For low normal stresses, mechanical difficulties associated with the precise control of normal stress may affect the accuracy of results, leading to nonconservative assessments of the interface shear strength. The inclined plane test is an alternative method to simulate field applications where the confining pressure acting on the soil-geosynthetic interface is generally low (e.g. landfill liner/cover systems and erosion protection systems).

Over recent decades, numerous experimental studies have been conducted to investigate the interaction behaviour of soil-geosynthetic and geosynthetic-geosynthetic interfaces through inclined plane and direct shear tests (e.g. Costa-Lopes et al. 2001, Gourc & Reyes Ramirez 2004, Bergado et al. 2006, Liu et al. 2009, Pitanga et al. 2009, Briançon et al. 2011, Vieira et al. 2013, Ferreira et al. 2012, 2013, 2014, 2015, Lopes et al. 2014). However, few studies have compared the interface shear strength properties evaluated from both test methods (Girard et al. 1990, Giroud et al. 1990, Koutsourais et al. 1991, Gourc et al. 1996, Izgin & Wasti 1998, Lalarakotoson et al. 1999, Wasti & Özdüzgün 2001, Reyes Ramirez & Gourc 2003).

Girard et al. (1990) studied an incident of partial slip that occurred during the construction of the Aubrac dam (France) along a geomembrane-geotextile interface. The authors used a large (375 mm × 375 mm) direct shear box, as well as a large (1000 mm × 1000 mm) inclined plane test device, to measure the friction at the geomembrane-geotextile interface. From the direct shear tests, which were conducted under normal stresses of 100 kPa, 200 kPa and 400 kPa, an interface friction angle of 34° was obtained, providing a considerable safety margin when compared with the inclination of the dam slope (21.8°). However, the friction angle measured through the inclined plane test was significantly lower (25°). The authors considered that the friction angle obtained using the inclined plane and the dynamic stresses resulting from vehicle traffic on the slope explained why the slip occurred.

Giroud et al. (1990) evaluated the shear strength of rough geomembrane-hard geonet and rough geomembrane-nonwoven geotextile interfaces through inclined plane and direct shear tests. In the direct shear tests, the interfaces were subjected to normal stresses between 25 kPa and 160 kPa. In the inclined plane tests, a much lower normal stress was applied (0.7 kPa). For the rough geomembrane-hard geonet interface, the shear strength parameters obtained from both test methods were identical. Conversely, for the rough geomembrane-nonwoven geotextile interface, the two types of test provided quite dissimilar results: the direct shear tests yielded values of interface friction angle and cohesion of 15° and 5.5 kPa, respectively, whereas in the inclined plane test the box slid at the inclination of 48°. The authors combined the data from both test methods to obtain a single interface strength envelope, which was found to have a curved shape for normal stresses below 25 kPa.

Izgin & Wasti (1998) compared results from inclined plane and direct shear tests conducted on various sand-geomembrane interfaces using the same interface area (60 mm × 60 mm). The inclined plane and direct shear tests were carried out under normal stress ranges of 5-50 kPa and 14-200 kPa, respectively. It was found that the interface shear strength versus normal stress relationships from the inclined plane tests could be represented by straight lines with almost negligible cohesion intercepts (up to 0.5 kPa). On the other hand, the strength envelopes resulting from the direct shear tests yielded higher friction angles (about 5-10°), as well as higher apparent cohesions, for the same interfaces. The authors concluded that direct shear tests may lead to nonconservative assessment of sand-geomembrane interface shear strength, particularly in situations where the normal stress at the interface is low.

Wasti & Özdüzgün (2001) extended the study by Izgin & Wasti (1998) using the inclined plane and direct shear test devices to evaluate the shear strength properties of several geomembrane-geotextile interfaces. The authors drew a parallel between the results obtained from the different test methods for distinct interface areas: 60 mm × 60 mm and 300 mm × 300 mm. The agreement between the results was found to depend on the type of interface. For smooth geomembrane–geotextile interfaces, a good agreement was achieved. However, for rough geomembrane–geotextile interfaces, direct shear tests yielded considerably higher interface shear strengths than those measured from inclined plane tests, as a result of the large cohesion values in the direct shear strength envelopes.

Reyes Ramirez & Gourc (2003) performed inclined plane and direct shear tests on a geotextile-geospacer interface. The direct shear tests were conducted under normal stresses of 25 kPa, 50 kPa and 75 kPa, using a 300 mm × 300 mm interface area, whereas the inclined plane test was conducted under initial normal stress of 5.7 kPa, with an interface area of 700 mm × 180 mm. The interface friction angle estimated from the inclined plane test (18.4°) was higher than that obtained from the direct shear tests (16.8°). This discrepancy was attributed to the different normal stresses under which the tests were conducted.

The review of the limited number of studies reported in the literature involving the use of the inclined plane, as well as the direct shear test, for the analysis of the same interfaces showed that the correlations between the results of the two types of test do not follow a general trend. This paper aims to provide a better insight into the relationship between soil-geosynthetic interface shear strength properties estimated from inclined plane and direct shear tests. Two different geosynthetics and a granite residual soil under different conditions of moisture content were selected for the study.

2. EXPERIMENTAL RESEARCH

2.1 Inclined Plane Test Device

The inclined plane test device used in this study (Figure 1) was developed at the University of Porto within the scope of previous research (Costa-Lopes et al. 2001). The apparatus consists of a dismountable structure that includes a rigid upper box (300 mm long, 300 mm wide and 80 mm high), a rigid lower box (510 mm long, 350 mm wide and 80 mm high) and a rigid base that can be inserted into the lower box. The inclination of the base plane during the test (0.5°/minute) is measured through an inclinometer and the relative displacement between the upper box and the geosynthetic is recorded by a transducer. The vertical force is applied by a rigid steel plate, covering the whole internal area of the upper box, which is connected to a hanger with weights. A load cell, located between the load beam and the rigid plate, is used to monitor the applied vertical force. More details about the test device and a description of the test procedures can be found in Lopes et al. (2014), Ferreira et al. (2014) and Ferreira (2015).

Fig. 1: Inclined plane test device

2.2 Direct Shear Test Device

The direct shear test device (Figure 2) was developed during previous research at the University of Porto (Vieira et al. 2013). The apparatus is composed of a shear box, divided into upper and lower boxes, a support structure, five hydraulic actuators and respective fluid power unit, an electric cabinet and several internal and external transducers. The inner length, width and thickness of the upper and lower boxes are 600 mm × 300 mm × 150 mm and 800 mm × 340 mm × 100 mm, respectively. The upper box is fixed in the horizontal direction and vertically moveable through hydraulic actuators installed on its edges. The lower box is rigidly fixed to a mobile platform running on low-friction linear guides and its horizontal displacement is controlled by a hydraulic actuator. The normal stress is applied by a rigid plate with pressure-controlled double acting linear actuators and recorded by a pressure transducer. The shear force applied in the lower box is measured by a load cell and its horizontal movement is recorded by an internal displacement transducer. The direct shear test device and test procedures are presented in detail by Vieira et al. (2013), Ferreira (2015) and Ferreira et al. (2015).

Fig. 2: Direct shear test device

2.3 Materials

2.3.1 *Soil*

The soil used in this study was a locally available granite residual soil, which is typically found in northern Portugal and often used as backfill material for reinforced soil construction. According to the Unified Soil Classification System, this soil may be classified as SW-SM (well-graded sand with silt and gravel). Figure 3 shows the soil particle size distribution curve and Table 1 presents its main physical properties.

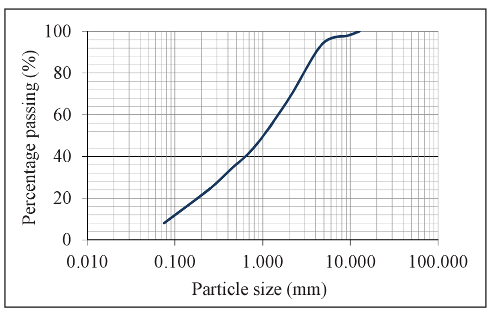

Fig. 3: Soil particle size distribution curve

Table 1: Soil physical properties

Property	**Value**
D_{10} (mm)	0.09
D_{30} (mm)	0.35
D_{50} (mm)	1.00
C_u	16.9
C_c	1.0
G_s	2.73
e_{max}	0.998
e_{min}	0.476
γ_{dmax}* (kN/m^3)	18.9
w_{opt}* (%)	11.5

* Obtained from the Modified Proctor Test (as per BS 1377-4:1990)

2.3.2 *Geosynthetics*

As previously mentioned, two geosynthetics were used in this study (Figure 4): a geocomposite reinforcement (GCR) and a uniaxial extruded geogrid (GGR). The geocomposite reinforcement (Figure

4a) consists of high-modulus polyester (PET) yarns, attached to a continuous filament nonwoven geotextile of polypropylene (PP). The uniaxial geogrid (Figure 4b) is manufactured from high density polyethylene (HDPE). The physical and mechanical properties of these materials are summarised in Table 2.

(a) (b)

Fig. 4: Visual aspect of the geosynthetics: (a) GCR; (b) GGR

Table 2: Physical and mechanical properties of the geosynthetics

Property	**GCR**	**GGR**
Raw material	PET/PP	HDPE
Mass per unit area (g/m^2)	310	450
Nominal thickness – 2kPa (mm)	2.3	-
Thickness of longitudinal ribs (mm)	-	1.1
Thickness of transverse ribs (mm)	-	2.7
Short term tensile strength* (kN/m)	58	68
Strain at maximum load* (%)	11.5	11.0
Short term tensile strength† (kN/m)	54.6	52.2
Strain at maximum load† (%)	10.6	12.4

* Provided by the manufacturer (machine direction)
† Obtained from tensile tests in the machine direction (as per EN ISO 10319:2008)

2.4 Test Programme

Inclined plane and direct shear tests on soil-geosynthetic interfaces were carried out in accordance with the European Standards EN ISO 12957-2:2005 and EN ISO 12957-1:2005, respectively. The inclined plane tests (IPT) were conducted under initial normal stresses of 5 kPa, 10 kPa and 25 kPa. Each test was carried out three times, as recommended by EN ISO 12957-2:2005. In the direct shear tests (DST), the specimens were subjected to normal stresses of 50 kPa, 100 kPa and 150 kPa. According to EN ISO 12957-1:2005, the tests were carried out twice for the normal stress of 100 kPa. The soil was compacted to the dry unit weight of 15.3 kN/m^3 under different moisture conditions: dry and with half of optimum (1/2 w_{opt}) and optimum (w_{opt}) moisture contents. Both geosynthetics were tested in contact with dry and moist soils. Thus, the study herein presented includes results from 54 inclined plane tests and 24 direct shear tests.

3. RESULTS AND DISCUSSION

3.1 Comparison of Shear Stress-shear Displacement Behaviour

The soil-geosynthetic direct shear test allows monitoring the evolution of the shear stress (τ) at the interface, induced by an imposed horizontal displacement, under constant normal stress conditions. The interface shear strength is usually determined as the maximum value of shear stress developed during the test and, as long as the allowable shear displacement is large enough, the residual shear strength of the interface can also be evaluated. On the other hand, the inclined plane test consists of increasing the inclination of the base plane until the soil block slides on the geosynthetic layer. As opposed to what occurs in the direct shear test, the normal stress at the interface decreases as the inclination of the base is progressively increased. The interface peak shear strength is estimated taking into account the inclination at which the upper box reaches a displacement of 50 mm (EN ISO 12957-2:2005). The strain softening behaviour and the residual interface strength cannot be evaluated, since non-stabilised sliding occurs for a constant inclination of the base. In view of the above considerations, when comparing results from inclined plane and direct shear tests, it is important to bear in mind the differences in test conditions and kinematics associated with these test methods.

As mentioned before, the inclined plane and direct shear tests were conducted under different normal stress levels. Thus, in order to directly compare the shear behaviour of the interfaces along both types of test, the shear stress-shear displacement curves were normalised with respect to normal stress (σ).

Figure 5 shows the shear displacement-normalised shear stress relationships obtained from inclined plane and direct shear tests on the soil-GCR interface, under different conditions of soil moisture content (w): dry (Figure 5a), half of optimum moisture content (Figure 5b) and optimum moisture content (Figure 5c). In turn, the results concerning the soil-GGR interface are plotted in Figure 6. The presented curves correspond to normal stresses ranging from 5 kPa to 25 kPa, for the inclined plane test, and 50 kPa to 150 kPa, for the direct shear test.

It is important to highlight that, for the inclined plane tests, the values of normal stress indicated in Figures 5-6 (5 kPa, 10 kPa and 25 kPa) refer to the initial normal stresses applied to the specimens. However, the normalised shear stress was computed taking into account the variation of the normal stress throughout the tests.

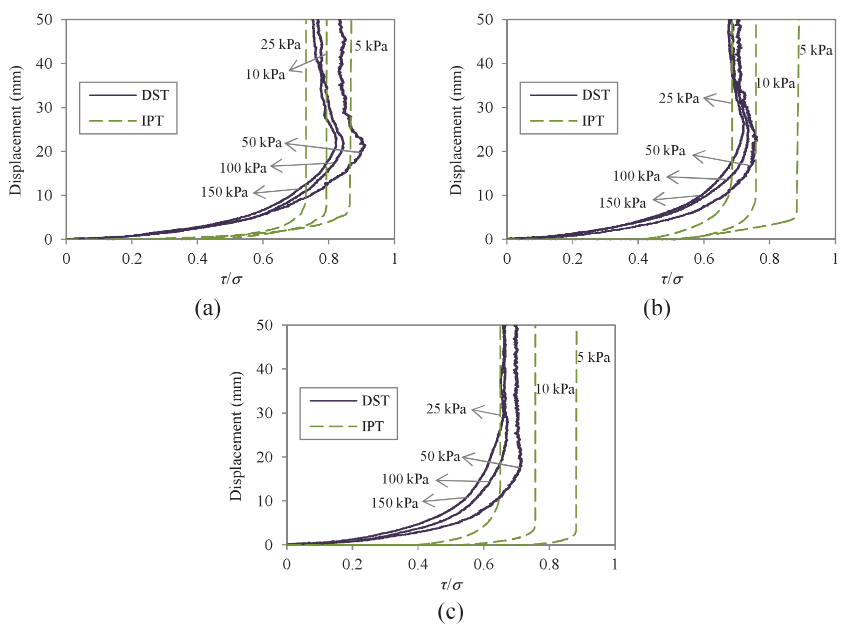

Fig. 5: Comparison of the displacement-normalised shear stress relationship from inclined plane and direct shear tests on soil-GCR interface: (a) dry soil; (b) $w = 1/2\ w_{opt}$; (c) $w = w_{opt}$

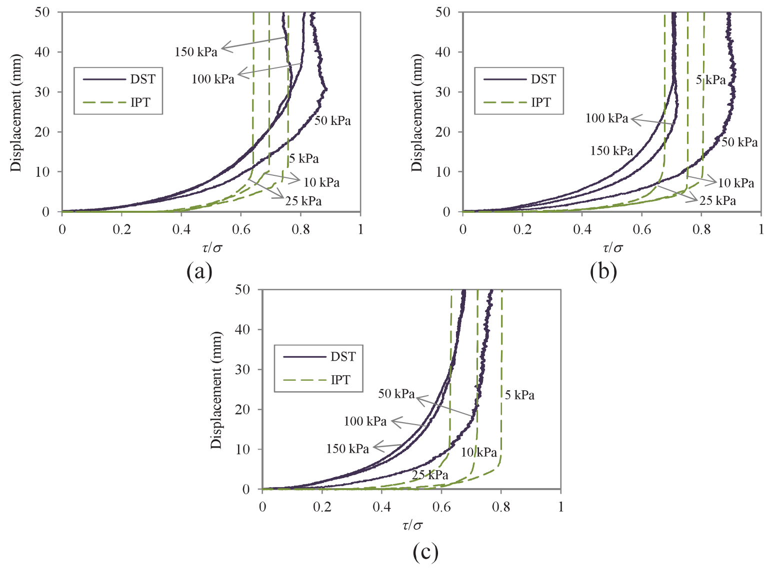

Fig. 6: Comparison of the displacement-normalised shear stress relationship from inclined plane and direct shear tests on soil-GGR interface: (a) dry soil; (b) $w = 1/2\ w_{opt}$; (c) $w = w_{opt}$

From Figures 5-6 it is possible to conclude that, for each test method, the normalised shear strength tends to decrease with the normal stress. The direct shear test results have demonstrated that, in general, the normalised shear strength for the normal stress of 50 kPa is considerably higher than that corresponding to the 100 kPa normal stress, whereas the difference between the normalised shear strengths for the normal stresses of 100 kPa and 150 kPa is generally of little importance. Conversely, the inclined plane test results have shown a progressive decrease in the normalised shear strength with the increase in the normal stress. However, when simultaneously considering the results from both test methods, no gradual reduction in the normalised shear strength with increasing normal stress is observed. This evidence may be attributed to the different methodologies associated with the two types of test.

The results in Figures 5-6 also show that, regardless of the interface, the displacement corresponding to the maximum shear stress is significantly lower in the inclined plane test, in comparison with that in the direct shear test

3.2 Comparison of Interface Shear Strength Parameters

The conventional method for determining the soil-geosynthetic interface shear strength parameters from direct shear test results is to fit a straight line through the plot of peak shear stress versus normal stress, which is referred to as the interface shear strength envelope. Based on the Mohr-Coulomb failure criterion, the values of the interface shear strength parameters, namely the interface friction angle (δ) and apparent cohesion (c_a), are derived. A similar analysis may be performed based on inclined plane test results, considering the shear stress and normal stress acting on the interface at failure (i.e. at the inclination for which the upper box reaches a displacement of 50 mm).

Figure 7 presents the shear strength envelopes obtained by linear regression analysis of the data from direct shear and inclined plane tests, conducted on the soil-GCR interface, for different soil moisture conditions: dry (Figure 7a), half of optimum moisture content (Figure 7b) and optimum moisture content (Figure 7c). Similarly, Figure 8 illustrates the shear strength envelopes derived from tests performed on the soil-GGR interface. Figures 7-8 include the values of the interface shear strength parameters (friction angle and apparent cohesion), as well as the coefficient of determination (R^2), corresponding to each strength envelope. It should be noted that, for comparison purposes, the shear strength envelopes have been extended for normal stresses below the range over which the tests were carried out.

Figures 7-8 indicate that, regardless of the soil moisture content and geosynthetic, the interface shear strength parameters estimated from direct shear tests were consistently higher than those resulting from inclined plane tests carried out under identical test conditions (i.e. soil moisture content and geosynthetic type). The interface friction angles determined from results of direct shear tests exceeded by up to 19.4% the values obtained from inclined plane tests. Regarding the interface cohesion, it can be observed that, whereas from the inclined plane tests, it was characterised by relatively low values (up to 1.2 kPa), which slightly increased with soil moisture content, from the direct shear tests the values were significantly higher (up to 12.0 kPa). These findings are in agreement with the results reported by Girard et al. (1990) for a geomembrane-geotextile interface, Izgin & Wasti (1998) for sand-geomembrane interfaces and Wasti & Özdüzgün (2001) for rough geomembrane–geotextile interfaces, in which the interface shear strength parameters obtained through direct shear tests have exceeded the values estimated from inclined plane tests. Therefore, it would have been nonconservative to extrapolate the straight-line relationship between shear strength and normal stress, established from direct shear test results, for normal stresses below the tested range. This evidence enhances the importance of performing inclined plane tests to evaluate the soil-geosynthetic interface shear strength under low normal stresses, particularly in cases where the interface is expected to experience low normal loads in the field, either during construction, or throughout the working life of the structure.

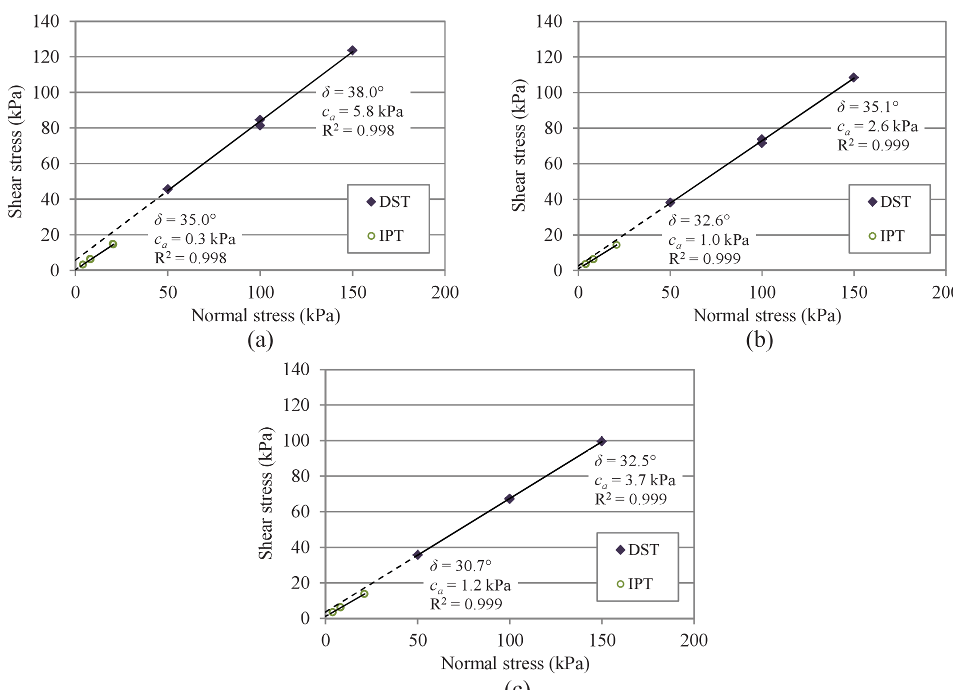

Fig. 7: Comparison of interface shear strength parameters estimated from inclined plane and direct shear tests on soil-GCR interface: (a) dry soil; (b) $w = 1/2\ w_{opt}$; (c) $w = w_{opt}$

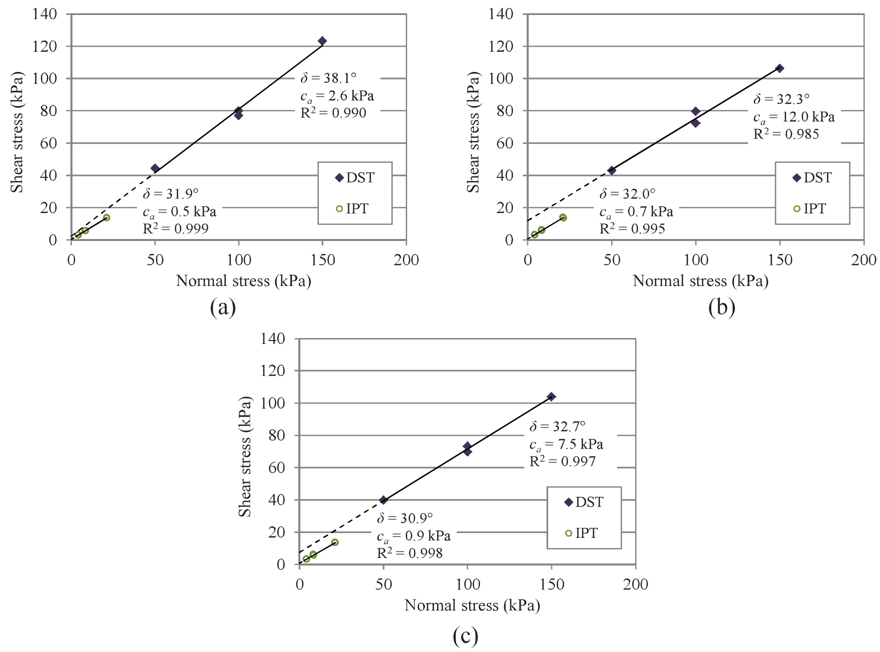

Fig. 8: Comparison of interface shear strength parameters estimated from inclined plane and direct shear tests on soil-GGR interface: (a) dry soil; (b) $w = 1/2\ w_{opt}$; (c) $w = w_{opt}$

3.3 Combination of Results From Both Test Methods

As mentioned previously, direct shear tests are commonly conducted under normal stresses greater than 50 kPa. Direct shear test results may, therefore, be complemented by results of inclined plane tests, which are typically carried out under low normal stress levels (Giroud et al. 1990).

Figure 9 combines the plots of peak shear stress as a function of normal stress, as measured in direct shear and inclined plane tests conducted on the soil-GCR interface, as well as the best-fit straight lines. Figure 9(a) presents results for the interface under dry conditions, whereas Figures 9(b) and 9(c) correspond to the half of optimum and optimum soil moisture contents, respectively. Analogous results concerning the soil-GGR interface are displayed in Figure 10.

Figures 9-10 reveal that, despite the differences in the normal stresses and kinematics associated with the different test methods, the results obtained for soil-geosynthetic interfaces under normal stresses ranging from 5 kPa to 150 kPa may be quite accurately represented by a single straight-line relationship between the shear strength and the normal stress. As shown in Figures 9-10, the interface friction angles determined through this approach were higher (up to 23.2%), while the apparent cohesions were lower than those defined from the individual analysis of results from the distinct methods. Indeed, while from the individual analysis, the cohesion values ranged from 0.3 kPa to 12.0 kPa, from the combination of results the values became almost negligible (≤ 0.6 kPa). These findings support the idea that the values of cohesion and friction angle derived from the inclined plane and direct shear tests should not be considered as real material properties, but simply as mathematical parameters used to describe the interface shear strength over the range of tested normal stresses.

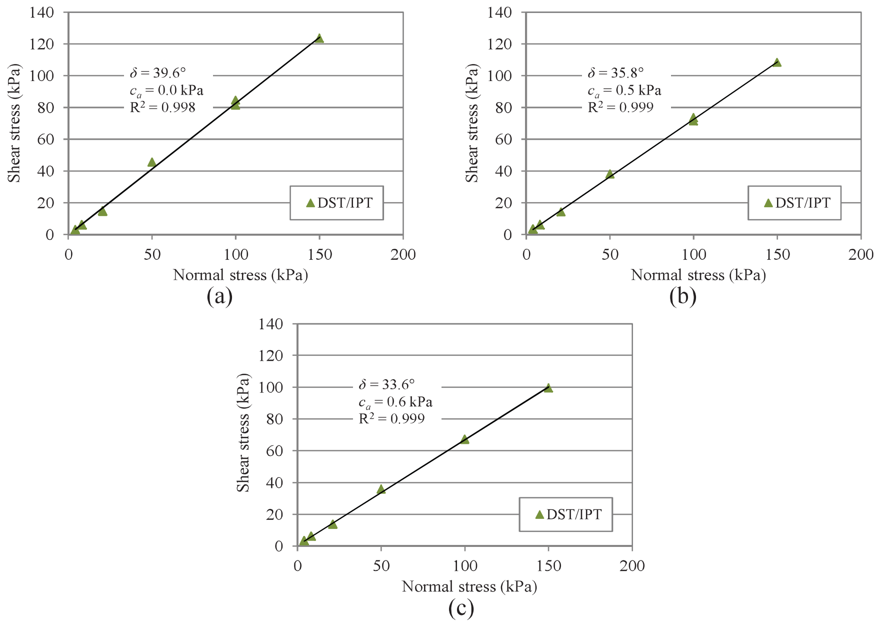

Fig. 9: Combination of results from inclined plane and direct shear tests on soil-GCR interface: (a) dry soil; (b) $w = 1/2\ w_{opt}$; (c) $w = w_{opt}$

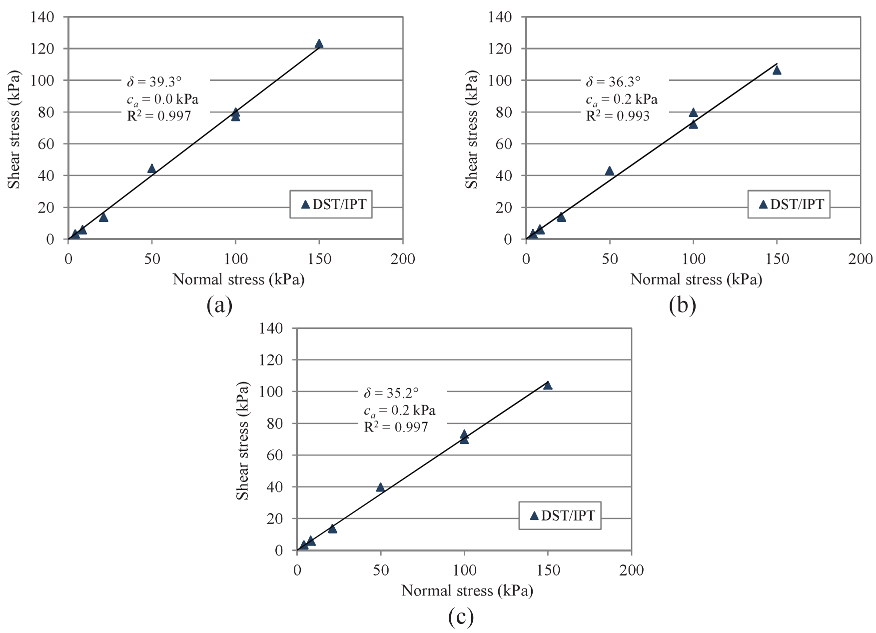

Fig. 10: Combination of results from inclined plane and direct shear tests on soil-GGR interface: (a) dry soil; (b) $w = 1/2\ w_{opt}$; (c) $w = w_{opt}$

4. CONCLUSIONS

This paper presents a comparison between soil-geosynthetic interface shear strength properties estimated from inclined plane and direct shear tests. Several interfaces involving a granite residual soil, under dry and moist conditions, and two different geosynthetics were analysed. The main conclusions of this study are summarised below.

The normalised shear stress-shear displacement curves have shown that, regardless of the interface tested, the displacement corresponding to the maximum shear stress in the inclined plane test was significantly lower than that in the direct shear test. For each test method, the normalised shear strength tended to decrease with the normal stress. However, considering the results for the whole range of tested normal stresses, no gradual reduction in the normalised shear strength with increasing normal stress was observed.

Direct shear tests have provided higher values of friction angle and apparent cohesion than those estimated by inclined plane tests. Therefore, it would have been nonconservative the extrapolation of the direct shear strength envelopes for normal stresses below the tested range (50-150 kPa).

The combination of results from direct shear and inclined plane tests has allowed to conclude that, despite the intrinsic differences in the normal stresses and kinematics, the soil-geosynthetic interface shear strength for a normal stress range of 5-150 kPa could be quite accurately described by the same Mohr-Coulomb shear strength envelope. This strength envelope was characterised by a higher friction angle and a lower cohesion intercept in comparison with the parameters derived from the individual analysis of results from the different test methods.

The conclusions herein presented were established from soil-geosynthetic interface tests conducted with a single value of soil dry unit weight. Further studies involving different values of soil dry unit weight would be useful to allow generalisation of the conclusions.

Acknowledgements

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