Soil–geosynthetic inclined plane shear behavior: influence of soil moisture content and geosynthetic type

Maria-Lurdes Lopes*, Fernanda Ferreira, José Ricardo Carneiro and Castorina Silva Vieira

This paper deals with the inclined plane shear on three different geosynthetics (a geocomposite (GC), a non-woven geotextile (GTX), and an extruded geogrid (GGR)) with a residual soil from granite. Soil and geosynthetic properties, test equipment, and procedures are described. The influence of soil moisture content and geosynthetic type on soil–geosynthetic interaction behavior is discussed by analyzing the results of the inclined plane shear tests. The main conclusions that can be outlined from the present study are the following: (1) the influence of soil moisture content was relevant for the soil–GTX and soil–GC interfaces. Indeed, the resistance of those interfaces decreased with the increase of soil moisture content. No significant differences were observed between the behavior of those geosynthetics; (2) the influence of soil moisture content on the behavior of the soil–GGR interface was less evident. A slight decrease on the interface friction angle was only observed for the highest soil moisture content; (3) the dry soil–GGR interface resistance was lower than that observed for the other two geosynthetics due to the relevance of soil–soil friction at the GGR apertures, to the high percentage of fines of the soil used in the research ($D_{50}=1{\cdot}00$ mm), and to the smoother solid lateral surface of the extruded GGR when compared with the surface of the GTX or GC.

Keywords: Geosynthetics, Soil–geosynthetic interaction, Inclined plane shear behavior, Soil moisture content

Notation

Basic SI units are given in parentheses.

β =slipping angle of upper box (°)
τ =shear stress (N m^{-2})
γ_d^{max} =maximum dry unit weight of soil (N m^{-3})
γ_d^{min} =minimum dry unit weight of soil (N m^{-3})
σ_n =normal stress (N m^{-2})
ϕ_{sg} =friction angle of soil–geosynthetic interface (°)
A =soil–geosynthetic contact area (m^2)
C_u =uniformity coefficient of soil (dimensionless)
C_c =curvature coefficient of soil (dimensionless)
D_{10} =diameter corresponding to 10% passing of soil (m)
D_{30} =diameter corresponding to 30% passing of soil (m)
D_{50} =diameter corresponding to 50% passing of soil (m)
$D_{máx}$ =maximum diameter of soil (m)
D_{min} =minimum diameter of soil (m)
$f_{(\beta)}$ =force required to restrain the empty upper box at inclination of β (N)
F_v =vertical force acting on soil–geosynthetic interface (N)
I_D =relative density of soil (%)
w_{opt} =Optimum soil moisture content (%)

Introduction

Inclined plane shear tests are used to characterize the interaction mechanism at soil–geosynthetic or geosynthetic–geosynthetic interfaces when the relative movement that occurs is of shearing and the geosynthetics are placed over an inclined surface.

Inclined plane shear behavior at soil–geosynthetic and geosynthetic–geosynthetic interfaces have been studied by several authors (among others: Izgin and Wasti, 1998;

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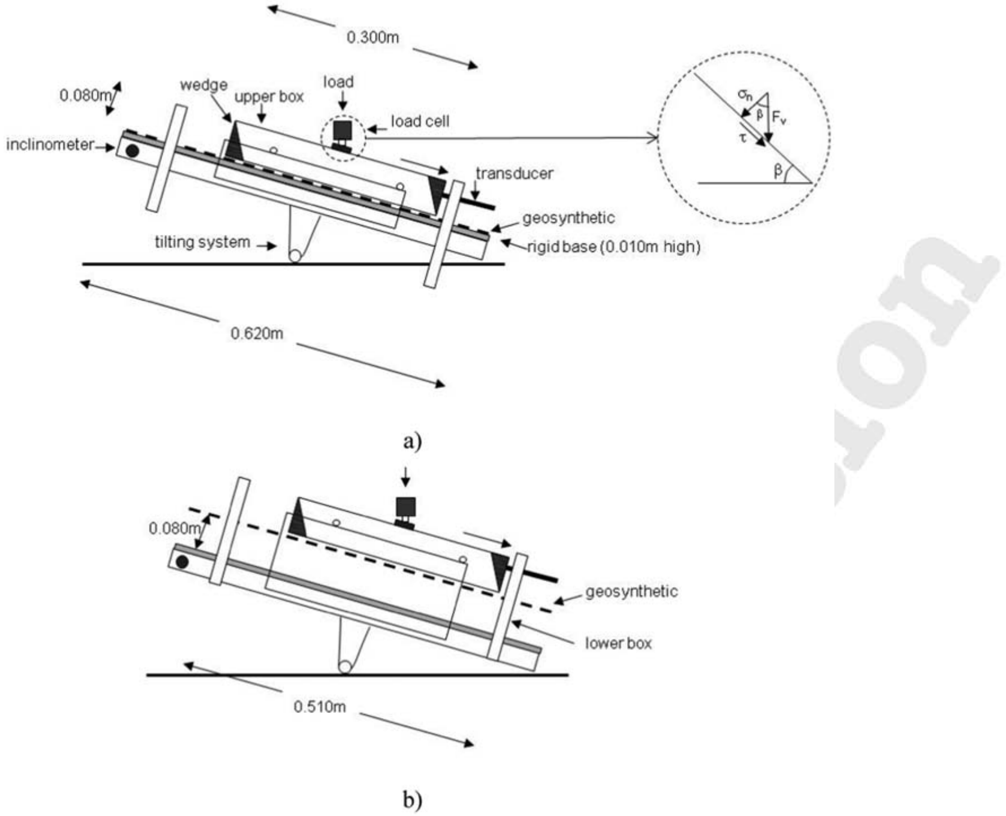


1 Schematic representation of the inclined plane shear test apparatus: *a* for test method 1 and *b* for test method 2

Wasti and Özdüzgün, 2001; Costa-Lopes *et al.*, 2001; Briançon *et al.*, 2002; Palmeira *et al.*, 2002; Reyes Ramirez and Gourc, 2003; Narejo, 2003; Pitanga *et al.*, 2009; Eid, 2011; Briançon *et al.*, 2011, Lopes, 2013).

With the aim of obtaining additional data on soil–geosynthetic interface behavior on inclined plane shear and on the influence on it of the soil moisture content and the geosynthetic type, this paper studies the interaction between different types of geosynthetics (a geocomposite (GC), a geotextile (GTX), and a geogrid (GGR)) and a residual soil from granite (with different moisture contents), by performing inclined plane shear tests according to EN ISO 12957-2 (Determination of friction characteristics. Part 2: inclined plane test).

Equipment and test procedures

The inclined plane shear test allows characterizing the resistance of soil–geosynthetic interfaces, by determining the minimum angle to the horizontal to which the sliding takes place between the soil and the geosynthetic.

The inclined plane shear test apparatus and test procedures used in the present research are exhaustively described in Costa-Lopes *et al.* (2001) and Lopes (2013).

The test can be carried out using two different methods:

1. with a rigid support for the geosynthetic (Fig. 1*a*);
2. with the geosynthetic supported on a lower box, which is filled with soil (Fig. 1*b*).

The inclined plane shear test apparatus (Fig. 1) is a dismountable structure that includes:

- a rigid and smooth base, 0·620 m long, 0·430 m wide, and 0·010 m high; the geosynthetic is placed on this base to carry out test method 1;
- a rigid lower box, with internal dimensions of 0·510 m long, 0·350 m wide, and 0·080 m high, that is filled with soil over which the geosynthetic is placed on test method 2;
- a rigid upper box, with internal dimensions of 0·300 m long, 0·300 m wide, and 0·080 m high, filled with soil that slides over the geosynthetic.

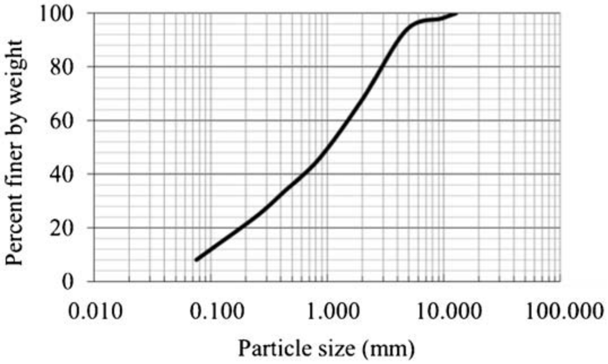
The rigid base can be raised at the rate of $0{\cdot}5^\circ\ \mathrm{min}^{-1}$ (test speed) and lowered, at the end of the test, at the rate of $2^\circ\ \mathrm{min}^{-1}$.

The normal force is applied by weights transmitted to a rigid steel plate that covers the whole interior area of the upper box. The assurance that the normal force passes through the center of gravity of the upper box is guaranteed by two wedges inclined one vertical to two horizontal and placed on the frontal and back walls of this box. A load cell, located between the load beam and the rigid plate, is used to measure the normal force applied.

The equipment includes three safety devices:

- one to stop the test when the movement of the upper box exceeds 0·050 m;
- the other two to stop the base when the maximum inclination of the equipment is reached and to stop the base at the horizontal position at the end of the test.

Costa-Lopes *et al.* (2001) concluded that soil–geosynthetic inclined plane shear behavior can be assessed by using test method 1 (with a rigid support for the geosynthetic) for geosynthetics with continuous lateral surfaces (e.g.: GTXs



2 Soil particle size distribution

or geomembranes). The authors suggested to use test method 2 (with the geosynthetic supported on a lower box which is filled with soil) for GGRs.

This way, in the present research, the inclined plane shear tests with the GC and GTX were performed according to test method 1 and the tests with the GGR were carried out according to test method 2.

The dimensions of the geosynthetic specimens were 0·70 m long and 0·43 m wide for test method 1 and 0·60 m long and 0·36 m wide for test method 2.

On test method 2, the soil was poured into the box from a constant height of 0·20 m and placed in 0·020 m thick layers. Each layer was leveled and compacted to the required density using a light compacting hammer.

After fixing the geosynthetic, the upper box was assembled and aligned in the starting position. The upper box was then filled with soil using procedures similar to the ones used in the lower box.

Table 1 Physical properties of the soil

Property	Unit	Value
D_{10}	mm	0·09
D_{30}	mm	0·35
D_{50}	mm	1·0
C_u	–	16·9
C_c	–	1·0
γ_d^{max}	kN m^{-3}	18·93
γ_d^{min}	kN m^{-3}	12·85
w_{opt}	%	11·45

The rigid plate was placed and the load applied.

Finally, the test speed was chosen, the horizontality of the base was verified and the transducer and the inclinometer were set to zero.

Materials

Soil

The soil used in this study was a well-graded residual soil from granite. According to the Unified Soil Classification System, this soil can be classified as SW-SM (well-graded sand with silt and gravel). Figure 2 shows the particle size distribution curve of the soil and its main physical properties are provided in Table 1. In order to take into account the difficulties in compacting soils in slopes, a conservative soil relative density (I_D) of 50% was considered. Different soil moisture contents were tested: dry, half of the optimum moisture content (1/2 w_{opt}), and optimum moisture content (w_{opt}).

Geosynthetics

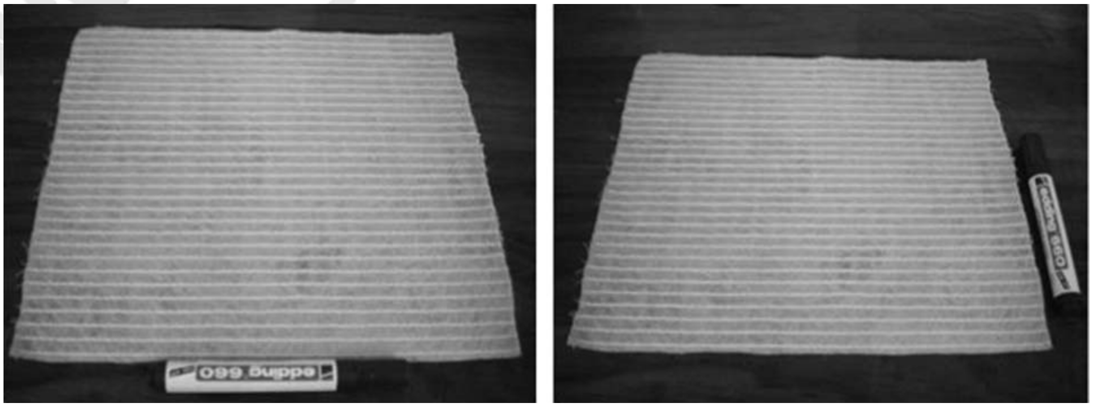
Three different geosynthetics were selected for this research: a GC, a non-woven spunbonded GTX, and a uniaxial extruded GGR.

The GC (Fig. 3) was composed of high modulus polyester (PET) fibers, attached to a continuous filament non-woven GTX backing; the GGR (Fig. 4) was manufactured from high-density polyethylene (HDPE); the GTX (Fig. 5) was made from mechanically bonded continuous filaments of polypropylene (PP). The main properties of the geosynthetics are summarized in Table 2.

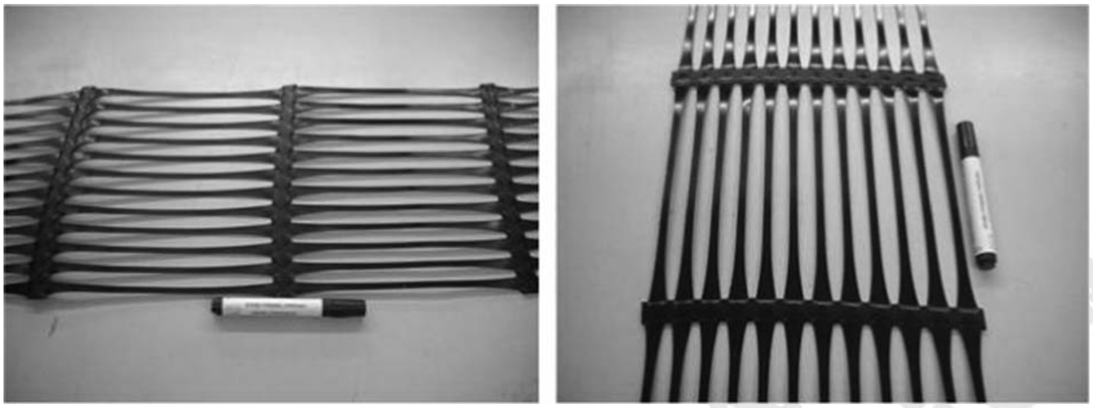
Test program

The program carried out in this study is shown in Table 3.

Each geosynthetic was tested under three vertical stresses (5, 10, and 25 kPa) and three soil moisture contents (dry, 1/2 w_{opt}, and w_{opt}). The GC was tested with the PET fibers along the shear direction. Although 27 tests are reported in Table 3, each one was repeated three times and, thus, a total of 81 tests were carried out.



3 Geocomposite



4 Extruded uniaxial geogrid

Results and discussion

Table 4 resumes the results of test T1 and Fig. 6 shows the variation of the upper box displacement with the inclination of the rigid base for the three specimens tested under the same conditions (GC, vertical stress of 5 kPa, dry soil).

The inclination for the maximum upper box displacement (50 mm) provides information about the slipping angle of the upper box, β, that allows deriving the friction angle of the interface, ϕ_{sg}.

The normal stress, σ_n, applied when the slipping angle of the upper box is equal to β can be obtained as follows:

$$\sigma_n = \frac{F_v \cos \beta}{A} \tag{1}$$

where F_v is the vertical force acting on the interface and A is the contact area.

The shear stress (τ) at the sliding surface is defined as:

$$\tau = \frac{F_v \sin \beta + f_{(\beta)}}{A} \tag{2}$$

where $f_{(\beta)}$ is the force required to restrain the empty upper box when the tilt table is inclined at the angle β.

It is possible to calculate the angle of friction of soil–geosynthetic interfaces, ϕ_{sg}, as follows:

$$\tan \phi_{sg} = \frac{\tau}{\sigma_n} \Rightarrow \phi_{sg} = \tan^{-1} \frac{\tau}{\sigma_n} \tag{3}$$

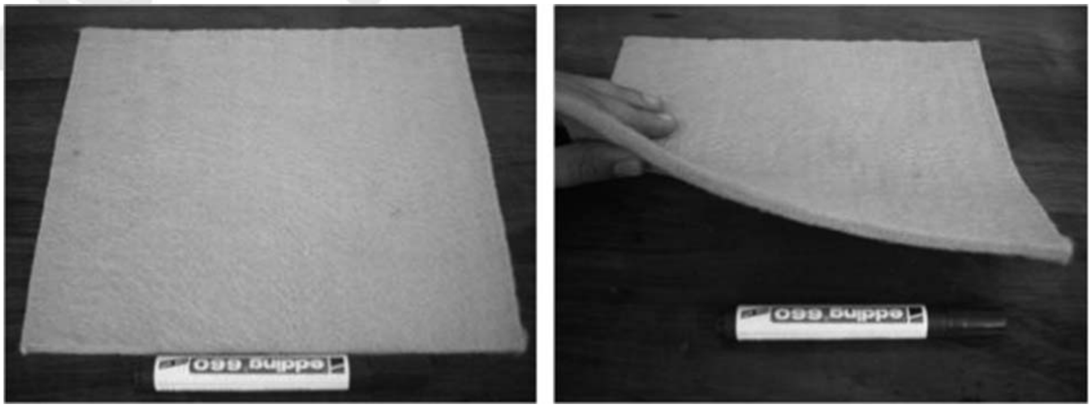
The mean friction angle on the interface between dry soil ($I_D = 50\%$) and the GC under a vertical stress of 5 kPa

Table 2 Physical and mechanical properties of the geosynthetics

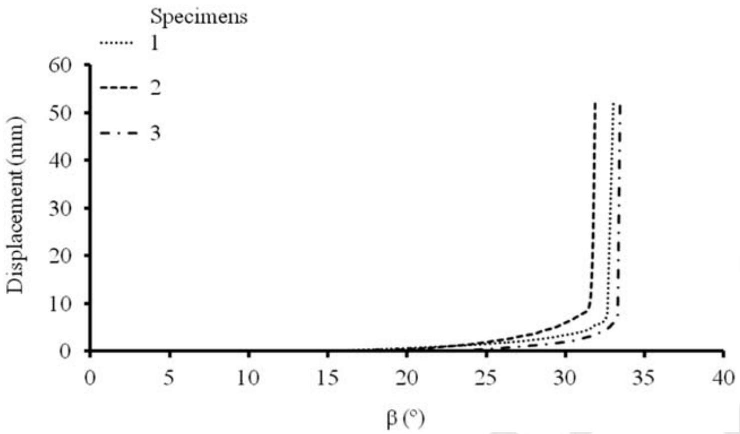
		Geosynthetics		
Property	Unit	GC	GGR	GTX
Raw material	–	PET/PP	HDPE	PP
Mass per unit area	$g\ m^{-2}$	310	450	1000
Mean aperture size	mm	–	16×219	–
Short term tensile strength[1]	$kN\ m^{-1}$	58	68	55
Short term tensile strength[2]	$kN\ m^{-1}$	54·6	52·2	69·5
Strain at maximum tensile strength[1]	%	11·5	11	105
Strain at maximum tensile strength[2]	%	10·6	12·4	100·9

[1] Provided by the manufacturer (machine direction).

[2] Obtained in tensile tests performed according to EN ISO 10319 (machine direction).



5 Non-woven geotextile



6 Dry soil–GC interface (test T1): variation of the measured upper box displacement with the inclination of the rigid base for the three specimens tested

was 37·0° with a standard deviation of 0·9° and a coefficient of variation of 2·4% (see Table 4).

Table 5 shows the mean values of the friction angles at soil–geosynthetic interfaces under different vertical stresses and soil moisture contents for the GC, the non-woven GTX, and the extruded GGR. The coefficients of variation obtained for those values did not exceed 5%.

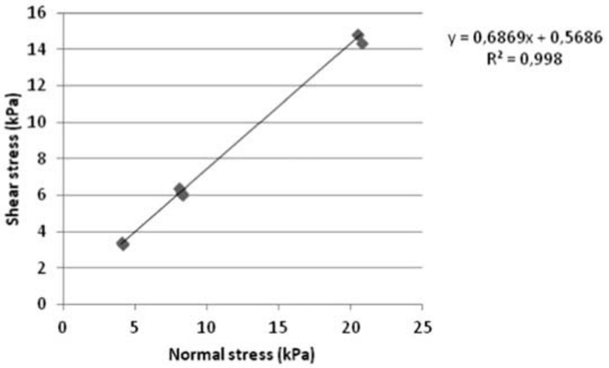
It can be seen that the friction angle at soil–geosynthetic interfaces decreased with the increase of the vertical stress. The GC and the non-woven GTX exhibited a similar behavior. The increase of soil moisture content induced a slight increase on the friction angle at soil–geosynthetic interfaces for the lowest vertical stress applied (5 kPa) and a slight decrease for the highest vertical stress used (25 kPa).

For the soil–GGR interface, the increase of soil moisture content induced a slight increase on the friction angle for 5 and 10 kPa of vertical stress. This tendency was not observed for the highest vertical stress used (25 kPa).

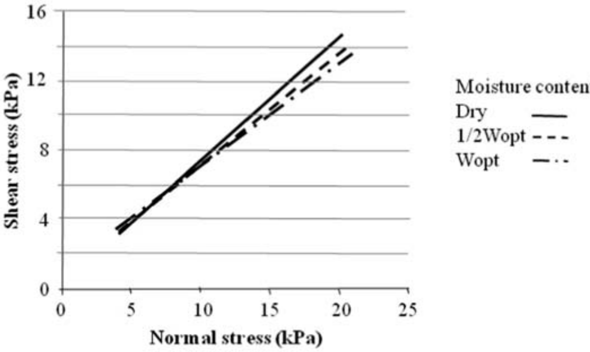
A different approach to define soil–geosynthetic interface parameters based on the results of inclined plane shear tests was considered.

Table 3 Test program

			Vertical stress/kPa			Soil moisture content (%)		
Test	Test method	Geosynthetic	5	10	25	Dry	1/2 w_{opt}	w_{opt}
T1	1	GC	X			X		
T2	1	GC		X		X		
T3	1	GC			X	X		
T4	1	GC	X				X	
T5	1	GC		X			X	
T6	1	GC			X		X	
T7	1	GC	X					X
T8	1	GC		X				X
T9	1	GC			X			X
T10	1	GTX	X			X		
T11	1	GTX		X		X		
T12	1	GTX			X	X		
T13	1	GTX	X				X	
T14	1	GTX		X			X	
T15	1	GTX			X		X	
T16	1	GTX	X					X
T17	1	GTX		X				X
T18	1	GTX			X			X
T19	2	GGR	X			X		
T20	2	GGR		X		X		
T21	2	GGR			X	X		
T22	2	GGR	X				X	
T23	2	GGR		X			X	
T24	2	GGR			X		X	
T25	2	GGR	X					X
T26	2	GGR		X				X
T27	2	GGR			X			X



7 Failure envelope for dry soil–geotextile (GTX) interface



8 Failure envelopes for soil–geocomposite (GC) interfaces

Table 4 Results of test T1 (geocomposite (GC), vertical stress of 5 kPa, dry soil)

Specimens	β/°	Fv/N	A/m^2	σ_n/kPa	$f(\beta)$/N	τ/kPa	τ/σ_n	ϕ_{sg}/°
1	33·0	450	0·09	4·19	41·63	3·19	0·76	37·3
2	31·9	450	0·09	4·25	40·37	3·09	0·73	36·0
3	33·5	450	0·09	4·17	42·10	3·23	0·77	37·7
Mean value	32·8							37·0
SD[1]	0·8							0·9
CV[2] (%)	2·4							2·4

[1] Standard deviation.
[2] Coefficient of variation.

Based on the values of normal and friction stresses of the three tests carried out with a geosynthetic and each value of soil moisture content, the failure envelope was defined (Fig. 7).

Tables 6 and 7 present the values of normal and friction stresses obtained on the inclined plane shear tests of, respectively, the non-woven GTX and the extruded GGR confined by soil with different moisture contents (dry, 1/2 w_{opt}, and w_{opt}).

Figure 8 shows the failure envelopes for soil–GC interfaces and Table 8 sums the soil–geosynthetic interfaces friction angle for all the conditions considered in the present research.

Table 5 Mean friction angles of the soil–geosynthetic interfaces

Vertical stress (kPa)	Mean friction angle/°								
	GC			GTX			GGR		
	Soil moisture content (%)								
	Dry	1/2 w_{opt}	w_{opt}	Dry	1/2 w_{opt}	w_{opt}	Dry	1/2 w_{opt}	w_{opt}
5	37·0	41·4	41·0	39·5	41·7	41·0	36·5	37·8	38·8
10	37·2	37·1	37·1	37·1	37·7	36·9	34·4	36·3	35·9
25	35·6	34·4	33·0	35·6	34·6	33·1	32·9	33·4	32·6

Table 6 Values of normal stresses and shear resistances of the soil–geotextile (GTX) interface

Vertical stress (kPa)	Specimen	Soil moisture content (%)					
		Dry		1/2 w_{opt}		w_{opt}	
		σ_n/kPa	τ/kPa	σ_n/kPa	τ/kPa	σ_n/kPa	τ/kPa
5	1	4·12	3·31	4·04	3·44	4·00	3·50
5	2	4·10	3·35	3·95	3·58	4·08	3·38
5	3	4·04	3·44	3·94	3·60	3·95	3·58
10	1	8·24	6·15	8·10	6·36	8·08	6·39
10	2	8·08	6·39	8·14	6·29	8·34	5·99
10	3	8·28	6·08	8·18	6·23	8·25	6·13
25	1	20·46	14·85	20·80	14·34	21·13	13·81
25	2	20·46	14·85	20·95	14·11	21·17	13·75
25	3	20·77	14·39	20·62	14·61	21·17	13·75

Table 7 Values of normal stresses and shear resistances of the soil–GGR interface

		Soil moisture content (%)					
		Dry		1/2 w_{opt}		w_{opt}	
Vertical stress (kPa)	Specimen	σn/kPa	τ/kPa	σn/kPa	τ/kPa	σn/kPa	τ/kPa
5	1	4·30	2·98	4·26	3·06	4·12	3·31
5	2	4·18	3·21	4·12	3·31	4·13	3·29
5	3	4·20	3·18	4·11	3·33	4·10	3·34
10	1	8·42	5·85	8·21	6·19	8·14	6·31
10	2	8·45	5·79	8·44	5·82	8·33	6·00
10	3	8·48	5·74	8·18	6·24	8·48	5·76
25	1	21·22	13·67	20·97	14·07	21·23	13·65
25	2	21·14	13·80	20·92	14·16	21·22	13·67
25	3	21·24	13·64	21·32	13·50	21·31	13·51

The friction angle at soil–geosynthetic interfaces (ϕ_{sg}) decreased with the increase of the moisture content of the soil for the GC and for the non-woven GTX. The influence of geosynthetic type on the interface resistance was negligible for those two materials.

The influence of the soil moisture content was less evident on the soil–GGR interface. In fact, similar values of the friction angle (ϕ_{sg}) were observed for dry and 1/2 w_{opt} soil moisture contents. For the highest soil moisture content (w_{opt}) a slight decrease of the friction angle was registered.

For the soil–GGR inclined plane shear resistance, the soil–soil friction at the GGR apertures is of utmost importance as the solid lateral surface of the geosynthetic is smaller than the apertures lateral surface. On the other hand, the solid lateral surface of the GGR is smoother than the lateral surface of the GC or GTX. Both conditions, associated with the high percentage of fines of the soil used (D_{50}=1·00 mm), justified the lower dry soil–GGR interface resistance when compared with the other dry soil–geosynthetic interfaces.

Conclusion

This paper deals with inclined plane shear on three different geosynthetics (a GC, a non-woven GTX, and an extruded GGR) with a residual soil from granite. The influence of soil moisture content and geosynthetic type on soil–geosynthetic interaction behavior in inclined plane shear was discussed by analyzing the results of the inclined plane shear tests.

Based on the presented results the main conclusions can be put forward.

- the influence of soil moisture content was relevant for the soil–GTX and soil–GC interfaces;
- in fact, in both cases the interface resistance decreased more than 10% when soil moisture content changed from dry to optimum (w_{opt});
- no significant differences were observed between the interfaces with the GC and with the GTX;
- the influence of soil moisture content on the behavior of the soil–GGR interface was less evident; only for the highest soil moisture content (w_{opt}) a slight decrease (about 3%) on the interface friction angle was observed;
- the dry soil–GGR interface resistance was lower than that observed for the GC and for the GTX due to the relevance of soil–soil friction at the GGR apertures, to the high percentage of fines of the soil used in the research (D_{50}=1·00 mm) and to the smoother solid lateral surface of the GGR when compared with that of the other two geosynthetics.

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Table 8 Friction angles of soil–geosynthetic interfaces obtained from failure envelops

	GC			GTX			GGR		
	Soil moisture content (%)								
interface parameter	Dry	1/2 w_{opt}	w_{opt}	Dry	1/2 w_{opt}	w_{opt}	Dry	1/2 w_{opt}	w_{opt}
ϕ_{sg} (°)	35·0	32·6	30·7	34·5	32·7	30·8	31·9	32·0	30·8

References

Briançon, L., Girard, H. and Gourc, J. P. 2011. A new procedure for measuring geosynthetic friction with an inclined plane, *Geotext. Geomembr.*, **29**, (5), 472–482.

Briançon, L., Girard, H. and Poulin, D. 2002. Slope stability of lining systems – experimental modelling of friction at geosynthetic interfaces, *Geotext. Geomembr.*, **20**, (3), 147–172.

Costa-Lopes, P. C., Lopes, M. L. and Lopes, M. P. 2001. The inclined plane shear behaviour of geosynthetics – influence of soil particles size and geosynthetic structure. *Geosynth. Int.*, **8**, (4), 327–342.

Eid, H. T. 2011. Shear strength of geosynthetic composite systems for design of landfill liner and cover slopes, *Geotext. Geomembr.*, **29**, (3), 335–344.

Izgin, M. and Wasti, Y. 1998. Geomembrane – sand interface frictional properties as determined by inclined board and shear box tests, *Geotext. Geomembr.*, **16**, (4), 207–219.

Lopes, M. L. 2013. Friction at geosynthetic interfaces on inclined plane shear, *Indian Geotech. J.*, **43**, (4), 321–330.

Narejo, D. B. 2003. A simple tilt table device to measure index friction angle of geosynthetics, *Geotext. Geomembr*., 21, (1), 49–57.

Palmeira, E. M., Lima, N. R. Jr. and Mello, L. G. R. 2002. Interaction between soils and geosynthetic layers in large-scale ramp tests, *Geosynth. Int.*, **9**, (2), 149–187.

Pitanga, H. N., Gourc, J. P. and Vilar, O. M. 2009. Interface shear strength of geosynthetics: evaluation and analysis of inclined plane tests, *Geotext. Geomembr.*, **27**, 6, 435–446.

Reyes Ramirez, R. and Gourc, J. P. 2003. Use of inclined plane test in measuring geosynthetic interface friction relationships, *Geosynth. Int.*, **10**, (5), 165–175.

Wasti, Y. and Özdüzgün, Z. B. 2001. Geomembrane-geotextile interface shear properties as determined by inclined board sand hear box tests, *Geotext. Geomembr.*, **19**, (1), 45–57.

STANDARDS

EN ISO 12957-2. 2004. Geotextiles and geotextile-related products – determination of friction characteristics – part 2: inclined plane test. European Committee for Standardization in collaboration with the International Standardization Organization, Brussels.

EN ISO 10319. 2008. Geosynthetics – wide-width tensile tests. European Committee for Standardization in collaboration with the International Standardization Organization, Brussels.