Parameters and conditions affecting friction angles in geosynthetic interfaces

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ABSTRACT: The use of drainage geocomposites (GCD) coupled with various geosynthetics has become a common practice in landfill covering and lining systems. The global stability of these systems is closely related to the interface shear strength, which, in his, is affect by many parameters and testing conditions. Therefore, the relevant evaluation of the interface friction angle is a key issue for the liners design and performance. From literature, one of the most suitable methods to investigate the geosynthetic interface shear strength under low pressures is the inclined plane device. This paper summarizes the results of an inclined plane test program carried on for three different types of interfaces, widely used in landfill lining systems: GCD – GCL (geosynthetic clay liner), GCD – GGR (geogrid) and GCD – GMT (reinforced geomat). Moreover, in the research the effects of dry and wet conditions and of progressive damage, induced by relative displacement, were investigated.

Keywords: inclined plane test, geomat, drainage geocomposite, geosynthetic clay liner, dry and wet conditions

1 INTRODUCTION

Many geotechnical and hydraulic works require the use of several typologies of geosynthetics with specific functions such as: reinforcement, filtration, drainage, barriers, separation and erosion control. To accomplish these functions, geosynthetics could be combined in multilayer systems: the interfaces between these materials may be crucial discontinuities since sliding may occur as consequence of an improper assessment of the interface shear strength (Blight, 2007; Palmeira, 2009; Eid, 2011).

Several inclined plane test have been performed in literature, to characterize the interface shear strength (Reyes Ramìrez and Gourc, 2003; Gourc and Reyes Ramìrez, 2004; Wu et al., 2008; Briançon et al., 2011; Carbone et al., 2015): this type of test can provide comprehensive results at low contact stress, whereas the direct shear test is widely used at medium-high contact stress (Delmas et al., 1979; Gilbert et al., 1996; Triplett and Fox 2001; Zornberg et al., 2005; Fox et al., 2006; Fox and Ross, 2011) and the pull-out test allows designing liners anchorage (Moraci and Recalcati, 2006; Cazzuffi et al., 2011; Moraci and Cardile, 2012; Moraci et al., 2014).

The inclined plane test, widespread in Europe, is subjected to a specific standardization (EN ISO 12957-2, 2005) and, as mentioned before, it may be more accurate respect to the direct shear test in determining the strength of geosynthetic interfaces at normal stress lower than 20 kPa (Wasti and Özdüzgün, 2001); for this reason this test is very suitable for the design of landfill covers.
Moreover, using the direct shear test it is difficult to study the shear strength reduction at large displacement being not the maximum device displacement large enough. For increasing the relative displacement, many monotonic tests or several cycles of reversed displacement may be performed on the same specimen.
The pull-out device is mainly used to study the strength mobilized at the interfaces of geosynthetics, such as geogrids, immersed into a confining soil: it allows measuring the overall strength resulting from the friction mobilized on both the upper and the lower sides. From this point of view the interface strength is influenced by two or even three dimensional soil-geosynthetic interaction effects.
The great variability of geomaterials available in the practical engineering influences the interface strength as well as its behaviour, so that sufficient data, for each type of interface, are not yet available in the literature, especially at low normal stress. This work aims to extend the database of experimental strength measures of various interfaces, highlighting the different behaviours during the tests, also in the perspective of a possible review of the European standardization. The paper summarizes the results of inclined plane tests carried out on three different groups of interfaces widely used in landfill cover lining systems: GCD (drainage geocomposite) – GCL (geosynthetic clay liner) and GCD – GGR (geogrid), GCD – GMT (reinforced geomat). Moreover, the research investigates the interface strength in wet and dry conditions, taking also into account the effect of progressive damage induced by relative displacement.

2 TEST DEVICE AND PROCEDURES

The experimentation on the interface friction was conducted by means of an inclined plane device, available at the geotechnical laboratory of the ICEA Department at the University of Padua. It consists of a tilting plane, above which a steel block, free to slide along the plane, can be placed. The first geosynthetic, involved in the interface, is fixed to the inclined plane while the second one is bound to the bottom of the sliding block. The inclined plane has a length of 1.10 m and width of 0.25 m while the block has a length of 0.35 m and a width of 0.20 m. The inclination of the plane can be varied between 0° and about 45°. In order to ensure a straight sliding, the block is constrained by lateral guides, without introducing significant additional friction (Fig. 1).
The adopted test procedure allowed to measure the friction angle according to three different modes, as described below. At the start of the test, the plane is horizontal; gradually, the inclination of the plane is increased at a constant rate, of about 3°/min, according with the indications of the EN ISO 12957-2 (2005). The tilting angle (β_0) at which the block starts to slide corresponds to the "first movement" angle of friction (φ_0). In static condition, the first movement friction angle equals the tilting angle reached by the plane:

$$\tan \varphi_0 = \tan \beta_0 \qquad (1)$$

Referring to this first movement, it should be noted that the different interfaces may exhibit very different behaviours. There are interfaces for which the start of the sliding can be easily identified because, as the angle β_0 is reached, a clearly accelerated motion starts ("sudden sliding" behavior). Conversely, in other interfaces, the definition of the φ_0 angle is more difficult because the motion evolves in a so slow manner to be almost imperceptible ("gradual sliding" behavior). In other cases small movements occur, but they are not necessarily linked to an incipient contact slip. In all these tests, to overcome the difficulties in the evaluation of φ_0 angle, it was adopted the solution of detecting the interface strength for a relative displacement of 1mm.

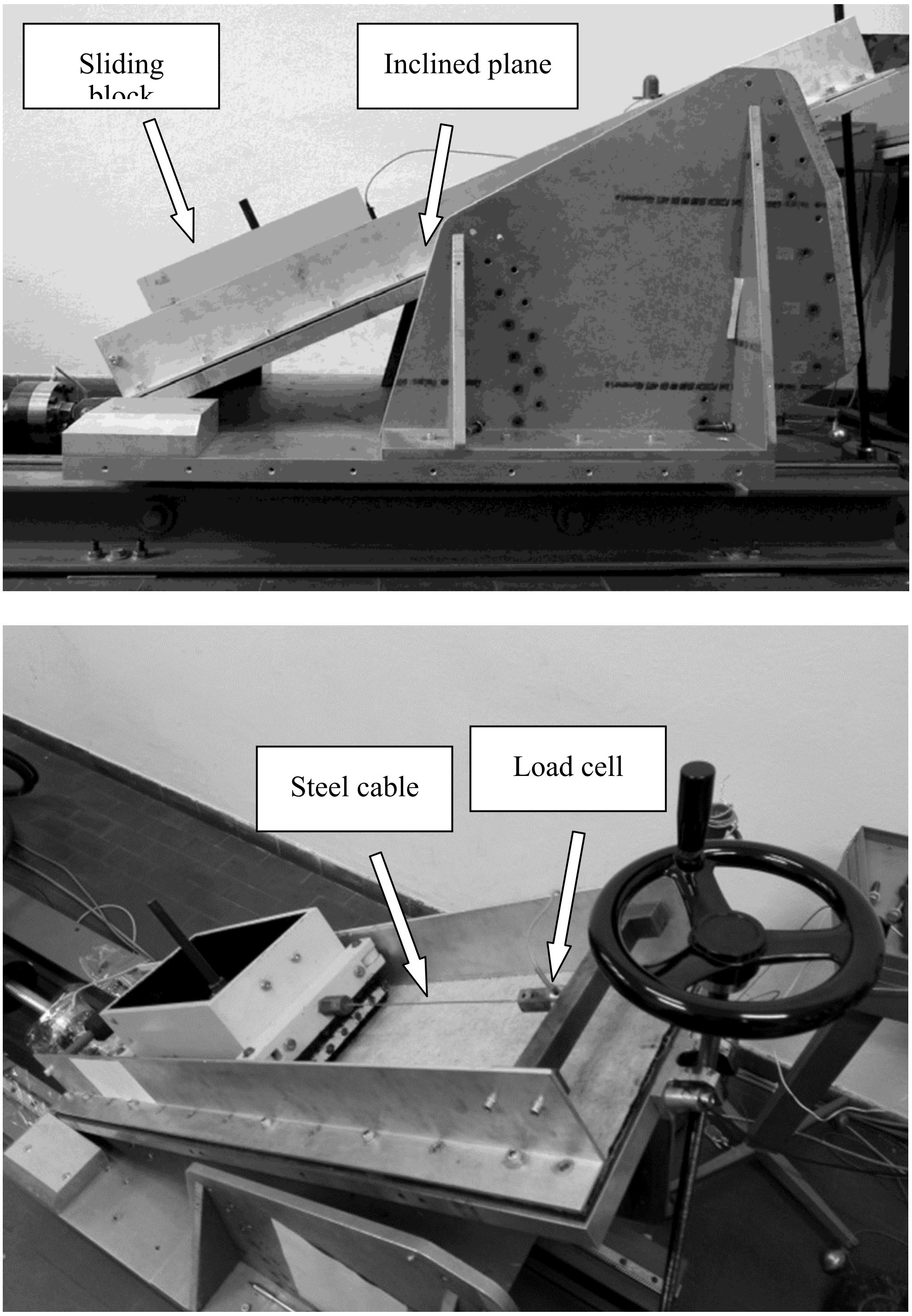

Figure 1. Inclined plane device available at the geotechnical laboratory of the ICEA Department of the University of Padua.

Once the first displacement has occurred, a second strength parameter is evaluated according to EN ISO 12957-2 (2005). To this purpose, whilst the plane inclination is varying, at a constant rate of 3°/min, the inclination reached for a cumulated displacement of 50 mm is detected; the so called φ_{st} ("standard friction angle") can be obtained from the following expression:

$$\tan\varphi_{st} = \tan\beta_{50} \tag{2}$$

However this 50 mm displacement is a conventional value, defined by the European Standard, not correlated to the pattern of the motion necessary to reach the required displacement; the same equation, giving φ_{st}, comes from the static equilibrium while the block is more properly in a kinematic condition, with velocity and acceleration not always negligible.
At the end of the test another strength parameter is evaluated by using the "force procedure" (Briançon et al., 2011): the sliding block is retained by a cable parallel to the plane and the force in the cable (F) is measured by means of a load cell. From the balance of forces, in static condition, a new parameter, here called limit friction angle (φ_{lim}), can be defined, according to the following expression:

$$\tan\varphi_{lim} = \tan\beta - \frac{F(\beta)}{W\cos\beta} \tag{3}$$

where W is the weight of the retained block.
Even if the plane inclination goes on, always with a constant velocity of 3°/min, the force changes in such a manner that φ_{lim} remains almost constant.

All the experiments were carried out at a vertical stress of 5 kPa and at a temperature in the range of 20°-24° C. For all the studied interfaces almost three different specimens were tested to outline a range of variability of the parameters.
A first measurement allowed to obtain φ_0 and φ_{st} of from virgin specimens. After a displacement of 300 mm it was measured also φ_{lim} for the first time, meaningful of a virgin specimen. In order to investigate the damage due to relative displacement, the test was repeated various times on the same specimen, by allowing the block to slide again from the starting position to obtain friction parameters related to the amount of the relative displacement cumulated. Almost 5 cycles were performed for each specimen.
Moreover, also wet conditions were investigated in some cases; to this regard, the specimens were immersed for 15 hours in water and, after dripping, subjected to the tests. At the end of the hydration phase, the water content of the GCL was about 300%.

3 STUDIED INTERFACES

The interfaces and the test conditions are summarized in Table 1: the first geosynthetic is the one fixed to the plane while the second is the one linked to the sliding block. In details, seven interfaces were studied coupling various geosynthetics: drainage geocomposite (GCD), geosynthetic clay liner (GCL), geogrid (GGR) and reinforced geomat (GMT), as shown in Fig. 2. For the interface GCD 1 / GCL, dry and wet conditions were also investigated.

Table 1. Studied interfaces and test conditions.

Case number	First geosynthetic	Second geosynthetic	Condition
1	GCD 1	GCL (woven face)	dry
2			wet
3	GCD 1	GCL (nonwoven face)	dry

4	GCD 2	GCL (nonwoven face)	dry
5	GCD 2	GGR	dry
6	GCD 2	GMA 1	dry
7	GCD 2	GMA 2	dry

GCD 1 and GCD 2 are two similar drainage geocomposites both formed by a draining body enclosed between two nonwoven geotextiles. The GCD 1 has a thickness of 7.2 mm under a pressure of 2 kPa and a mass per unit area of 740 g/m^2 while GCD 2 has a thickness of 6.1 mm under a pressure of 2 kPa and a mass per unit area of 670 g/m^2.

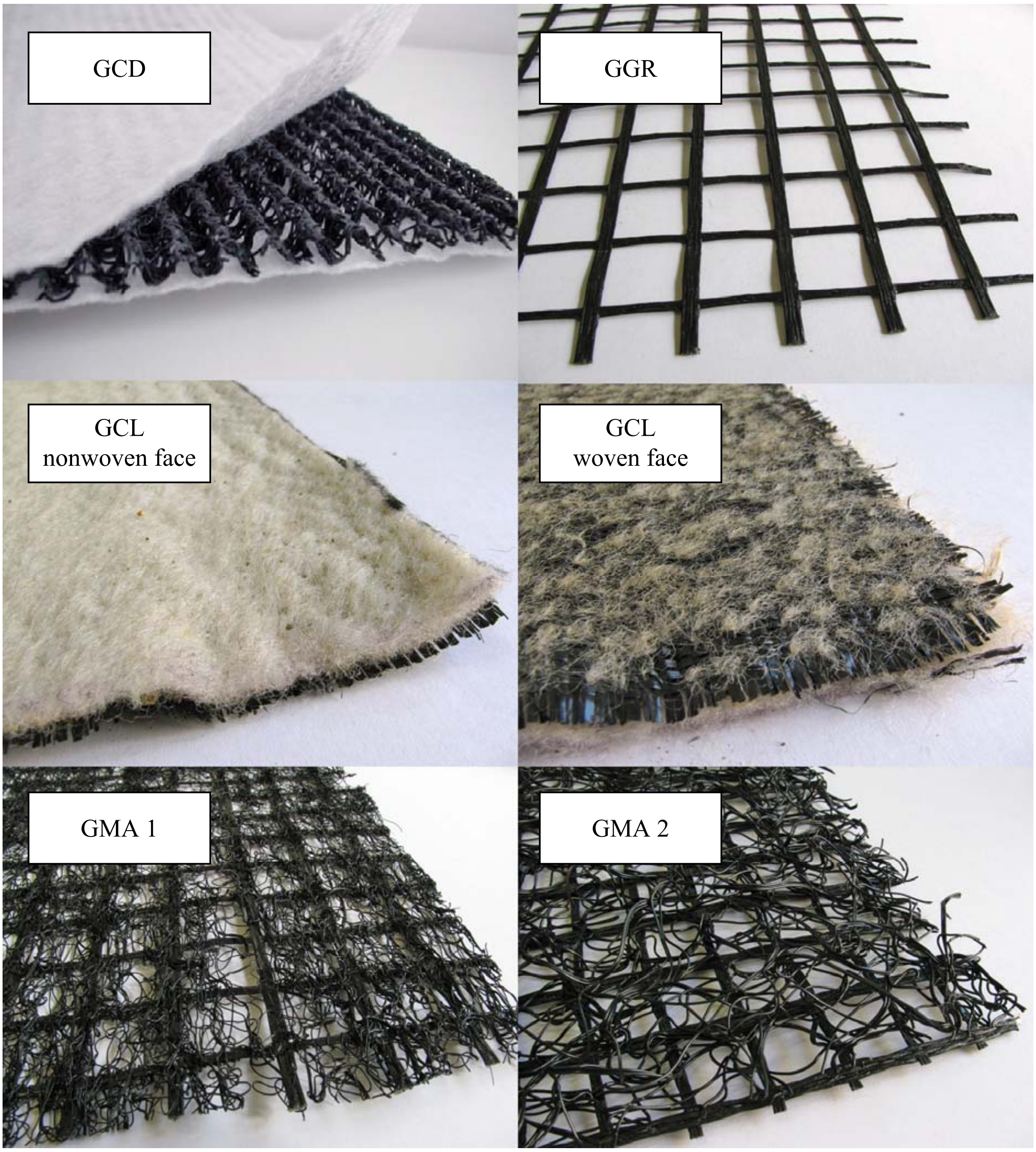

Figure 2. Different geosynthetics studied in this research.

GCL is a geosynthetic clay liner formed by two different geotextiles, one woven and one nonwoven, including a bentonite layer. The overall thickness is of 6 mm and the mass per unit area is of 4300 g/m^2.
GGR is a polyester geogrid with polymeric coating. The mesh is 30 × 30 mm and the nominal tensile strength is equal to 90 kN/m, in the length direction (MD), and to 35 kN/m in the transverse direction (CMD).
GMA 1 is a composite for soil reinforcement, made by a woven geogrid from high tenacity polyester multifilament yarns, protected by a polymeric coating, characterized by an improved adherence obtained by extruded on it a multifilament polyolefin three-dimensional mat. The mesh of the geogrid is 30 × 30 mm wide; the overall thickness is of 7 mm and the mass per unit area is of 520 g/m^2. The nominal tensile strength MD is equal to 90 kN/m and to 35 kN/m in the CMD.
GMA 2 is another polypropylene geomat, coupled with a woven geogrid as reinforcement, done by polyester yarns core with a polymeric protective coating. The mesh of the geogrid is 25 × 25 mm wide; the overall thickness is of 15 mm and the mass per unit area is of 790 g/m^2. The nominal mechanical strength in the longitudinal direction is equal to 80 kN/m.
During tests, the geomats GMA 1 and GMA 2 have been arranged according to the operative conditions, which implies that the geogrid included into the GMAs is directly in contact with the draining geocomposite GCD, while the mat is on the other side. In this study, no filling soil has been used for GMAs.

4 INCLINED PLANE TEST RESULTS

In the following, a comparison of inclined plane test results is presented for all the studied interfaces.
The test results for the first and the second case (GCD 1 / GCL - woven face, dry and wet conditions) are shown in Fig. 3 in terms of evolution of interface friction angle φ_0 versus cumulated displacement, while the analogous representations for φ_{st} and for φ_{lim} are shown in Fig. 4.
All these friction parameters show a visible reduction from dry to wet conditions from about 5°-6°, for φ_0 and for φ_{lim}, until 7°-10° for φ_{st}. The data dispersion is more pronounced for φ_0 in dry condition (about 5°) and minimum for φ_{lim}, in both dry and wet conditions; in this latter case the dispersion not exceeds 1°.
All the three parameter of friction show a low dependence from cumulated displacements, indicating a low sensitivity of the interface to the damaging.
It is important to highlight how φ_{st} is always greater than the other two parameters while φ_{lim} is always the lower. The difference between φ_{st} and φ_{lim} is of about 7° in dry condition and of about 4° in wet condition.

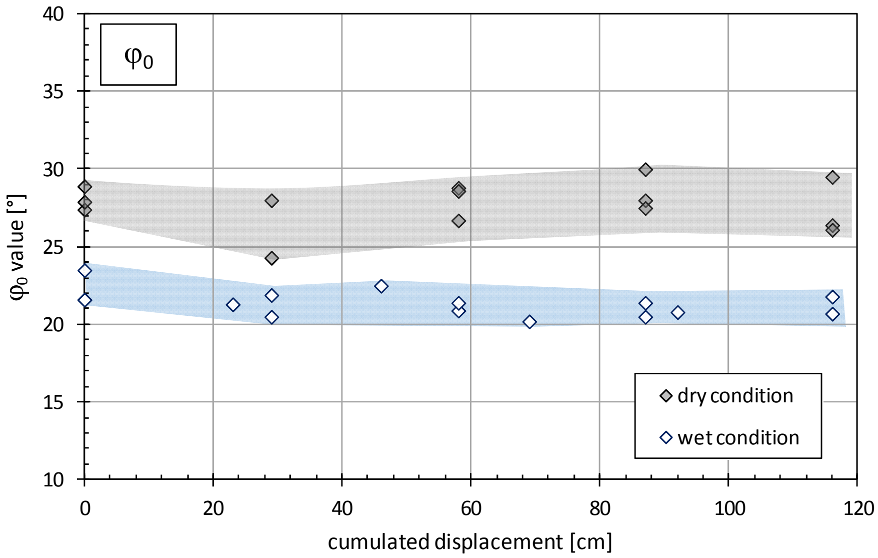

Figure 3 Interface friction angle φ_0 versus cumulated displacement (1st and 2nd cases, GCD 1 / GCL woven face).

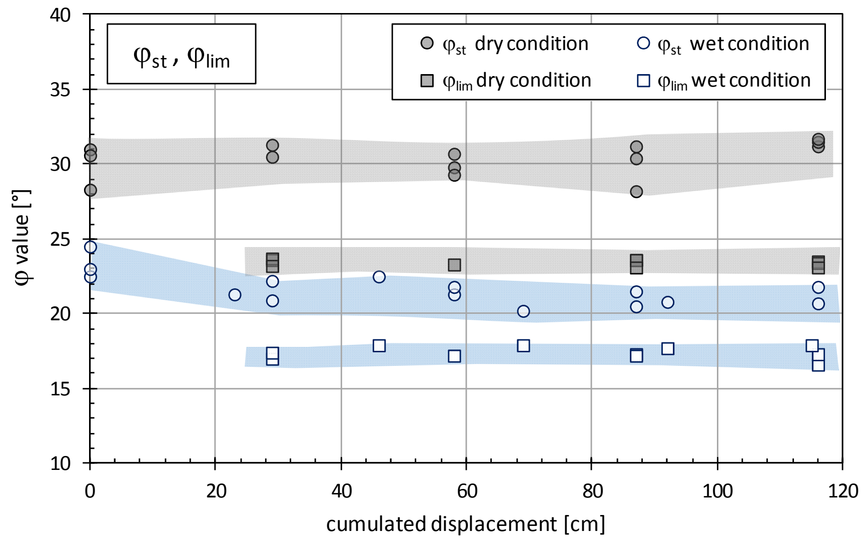

Figure 4. Interface friction angle φst and φlim versus cumulated displacement (1st and 2nd cases, GCD 1 / GCL woven face)

The results related to the third case (GCD 1 / GCL - nonwoven face, dry condition) are shown in Fig. 5. Also in this case φ_{st} is always greater than φ_0, but the difference is decreasing as the damaging increases. However, both φ_0 and φ_{st} increase, up to 4° with the progressive displacements. The parameter φ_{lim} is always the lower and remains constant with respect to cumulated displacements.
A comparison of results for the fourth case is presented in Fig. 6 (GCD 2 / GCL - nonwoven, dry condition), in which φ_0, φ_{st} and φ_{lim} have been represented together.
In this case φ_{st} is coincident with φ_0, and both show a pronounced decrease as displacements increase, as result of the mechanical damage. The coincidence of first movement friction an-

gle with standard friction angle is meaningful of a sudden sliding behaviour. The parameter φ_{lim} is always the lower and remains constant with respect to cumulated displacements.

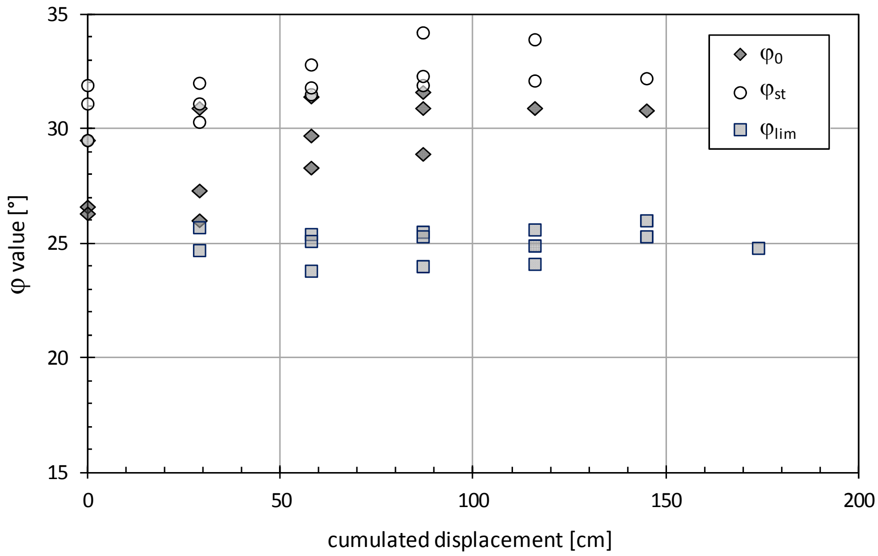

Figure 5. Interface friction angle φ_0, φ_{st} and φ_{lim} versus cumulated displacement (3[th] case, GCD 1 / GCL nonwoven face).

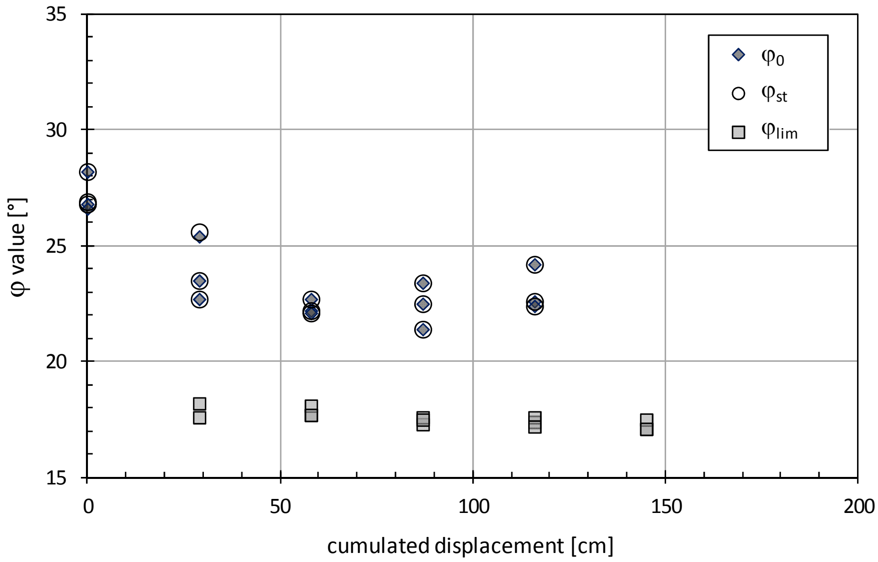

Figure 6. Interface friction angle φ_0, φ_{st} and φ_{lim} versus cumulated displacement (4[th] case, GCD 2 / GCL nonwoven face).

A comparison of results for the fifth case is presented in Fig. 7 (GCD 2 / GGR, dry condition), in which φ_0, φ_{st} and φ_{lim} have been represented together.
For this interface it is more evident the difference between φ_{st} and φ_0, indicating a gradual sliding behaviour. Once the inclination β_0 is reached, the motion starts at very low velocity so the time required to the block to reach a displacement of 50 mm allows a substantially increase of the slope angle ($\beta_{50} >> \beta_0$).

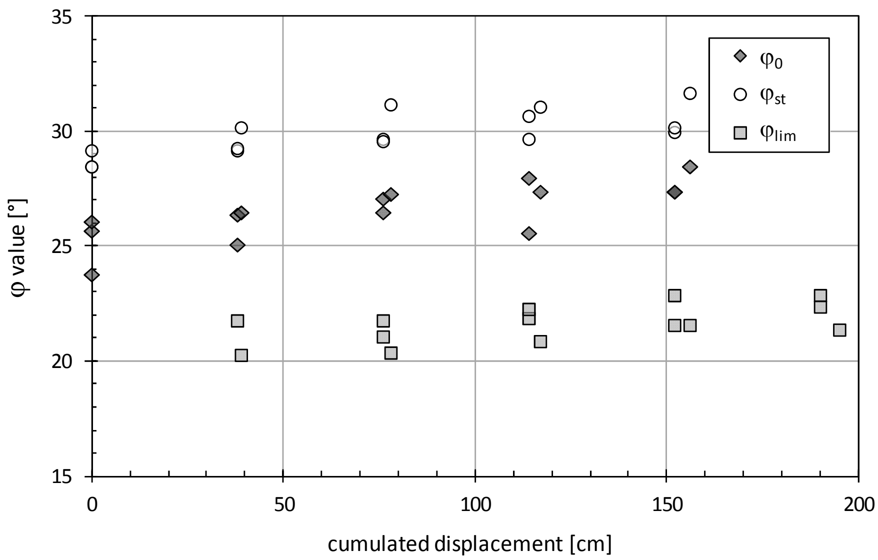

Figure 7. Interface friction angle φ_0, φ_{st} and φ_{lim} versus cumulated displacement (5th case, GCD 2 / GGR).

This circumstance is due to the mobilization of a viscous force at the interface, depending on the velocity of motion of the block. The difference, not depending on damaging, is of about 4° therefore, the application of the EN ISO 12957-2 (2005) is not conservative in this case. Moreover all the friction angles slightly increase as damaging increases (i.e. as the relative displacement increases).

A comparison of results for the sixth case is presented in Fig. 8 (GCD 2 / GMA 1, dry condition), in which φ_0, φ_{st} and φ_{lim} have been represented together.

Also in this case the values of φ_0, are lower than those of φ_{st} being the interface behaviour of the gradual sliding type. The difference, of about 3°, appears independent on the cumulated displacement.

Finally, a comparison of results for the seventh case is presented in Fig. 9 (GCD 2 / GMA 2, dry condition), in which φ_0, φ_{st} and φ_{lim} have been represented together.

Apart from the tendency of showing greater values of φ_{st} respect to φ_0, of about 4°-5°, in this interface the values of φ_{lim} are similar to those of φ_0. All the friction parameters show, in this case, a sensible dispersion which is more evident for φ_0.

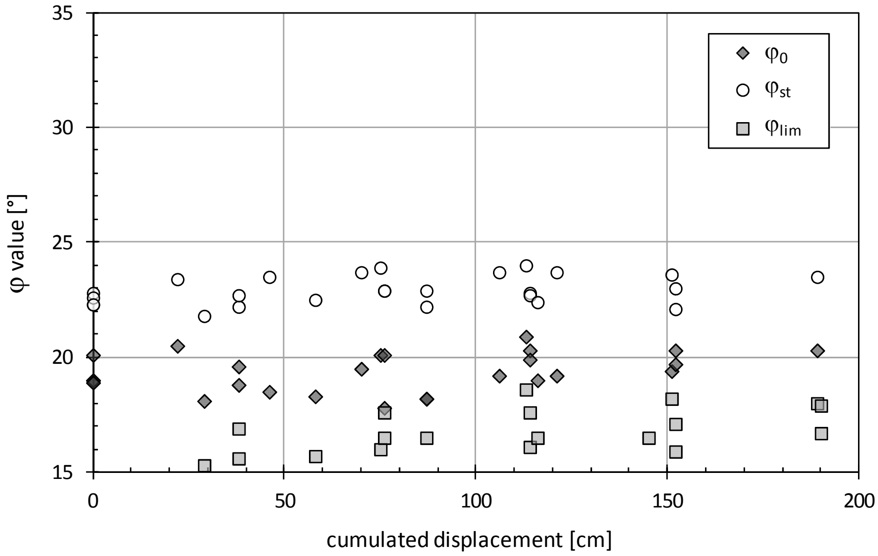

Figure 8. Interface friction angle φ_0, φ_{st} and φ_{lim} versus cumulated displacement (6th case, GCD 2 / GMA 1).

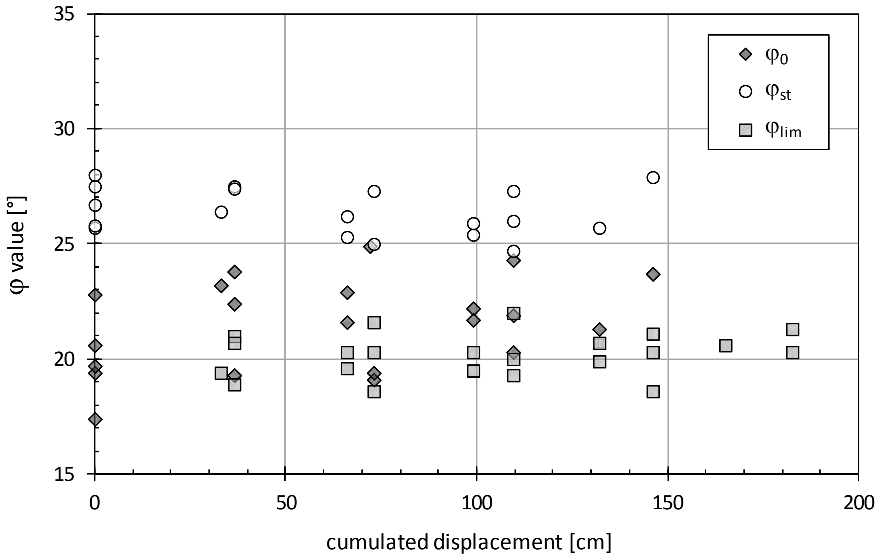

Figure 9. Interface friction angle φ_0, φ_{st} and φ_{lim} versus cumulated displacement (7th case, GCD 2 / GMA 2).

5 DISCUSSION AND CONCLUSIONS

The inclined plane tests carried out for seven geosynthetic interfaces under different conditions have highlighted some aspects discussed in the following.

The standard angle of friction, as defined by EN ISO 12957-2 (2005), gives always less conservative parameters (values of φ_{st} higher than φ_0) when the sliding mode is of the gradual type. Otherwise, when the sliding mode is of the sudden type both standard and first movement angles of friction are almost the same (as it happens in the 4th case, for example).

All the tested interfaces are not much sensitive to damaging caused by progressive displacements with the only exception of the contact between nonwoven face of the GCL and the nonwoven geotextile of the GCD 2.

The presence of water at the interface is able to reduce the mobilized interface friction. For example, for the interface between GCD 1 and the woven face of GCL, the reduction of friction from dry to wet conditions, is of about 5°- 6°, for φ_0 and φ_{lim}, and of about 7°-10° for φ_{st}.
The limit angle of friction is rather stable because it does not depend on the cumulated displacements and it shows the lower dispersion of data respect to the mean value. The difference between standard and limit angle of friction may be significant; it may range between 4° and 9° in relation to the analyzed interface.
Furthermore, in view of the above listed results, it appears that φ_0 should be used with a relatively high safety factor, while φ_{lim} may be used with a lower one.
Given the wide range of friction angles obtained in this work, further researches are required to investigate the interface behavior in condition comparable with the real working one. Referring to the interfaces involved the geogrid or the geomats, it should be observed that some differences in the interface strength occur when testing GGR, GMA 1 and GMA 2 in contact with the GCD 2. From this point of view these preliminary tests should be integrated by others including the veneer cover soil, to highlight further interactions induced by the soil presence.
In the Authors opinion, the most important finding of the research is the fact that φ_{lim} is practically independent from the displacement. Moreover, it can be considered a reliable lower bound value of the interface friction range outlined by all the various testing procedures, whereas practical design of multilayer systems usually refers to φ_0.

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