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The characterisation of geosynthetic interface friction by means of the inclined plane test

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A R T I C L E I N F O

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A B S T R A C T

The paper focuses on the evaluation of the shear strength in conditions of low normal stress of various geosynthetic-geosynthetic interfaces, which are typical of landfill cover systems, by means of the inclined plane test, with the aim of studying the friction mobilisation in relation to various kinematic behaviours. The results of three different methods to evaluate the angle of friction were analysed, together with the sensitivity of the interfaces in relation to the wear effect and the influence of the state of hydration. The results showed very different responses of the interfaces to the shear stress, which involved three main types of sliding mechanisms, referred to as sudden, gradual and uneven sliding. Another outcome observed was that the shear strength of geosynthetic-geosynthetic interfaces cannot always be properly characterised following the procedure proposed by the European standard for soil-geosynthetic interfaces (EN ISO 12957–2), since the actual mobilised kinematic behaviour should be taken into consideration. In this regard, the paper provides some hints on the choice of the more representative parameter of friction for each type of sliding. A particular focus was given to the case of gradual sliding interfaces, for which the static friction is difficult to detect due to the very slow movements; for practical purposes, the design friction of these interfaces should be evaluated by using an adequate safety factor with respect to the friction evaluated at 1 mm of displacement.

1. Introduction

Landfill cover systems are usually characterised by a series of geosynthetic interfaces having different functions. In a typical configuration, beneath the cover soil, there may be a reinforcement, a geogrid or a reinforced geomat (GMA), to ensure strength against the gravity forces, coupled with a drainage geocomposite (GCD), to drain the rainfall water, as well as a geomembrane (GMB) to prevent the intrusion and emission of fluids towards and from the waste material. The geomembrane may be accompanied by a geosynthetic clay liner (GCL), having the function of self-repair in the case of accidental puncturing of the geomembrane, and finally by a drainage geocomposite, which may be used to collect the biogas, or, alternatively, by a nonwoven geotextile that can be placed as a protective layer. The series of geosynthetic interfaces should thus be correctly characterised, also considering that conditions of low normal stress may exist even at less than 10 kPa.

In several geotechnical applications, such as in the case of landfill cover systems, the knowledge of the friction that is present at the interface between geosynthetics and between soil and geosynthetics is thus crucial in the design of the contact surfaces, since these interfaces represent potential slip surfaces. It comes without saying that a failure may occur if the stability of a composite system on a slope is not properly addressed, as has been previously reported in the literature (Blight, 2007; Stark et al., 2008; Wu et al., 2008; Eid, 2011).

The assessment of the available friction angle of the interface can be carried out by means of different types of tests (Palmeira, 2009; Moraci et al., 2014), which refer to the mechanisms of possible failure. The direct shear test is the one normally used to simulate the sliding along a slip surface, although the inclined plane test has been at the centre of attention in more recent times, more specifically in studies focused on conditions of low normal stress, since it is able to provide supplementary information on the behaviour of the interface. Various comparative studies on both tests have shown the inclined plane test to be suitable in determining the friction angle of the interface in conditions of low normal stress, also suggesting that it generally provides more precautionary results (Izgin and Wasti, 1998; Lalarakotoson et al., 1999; Wasti

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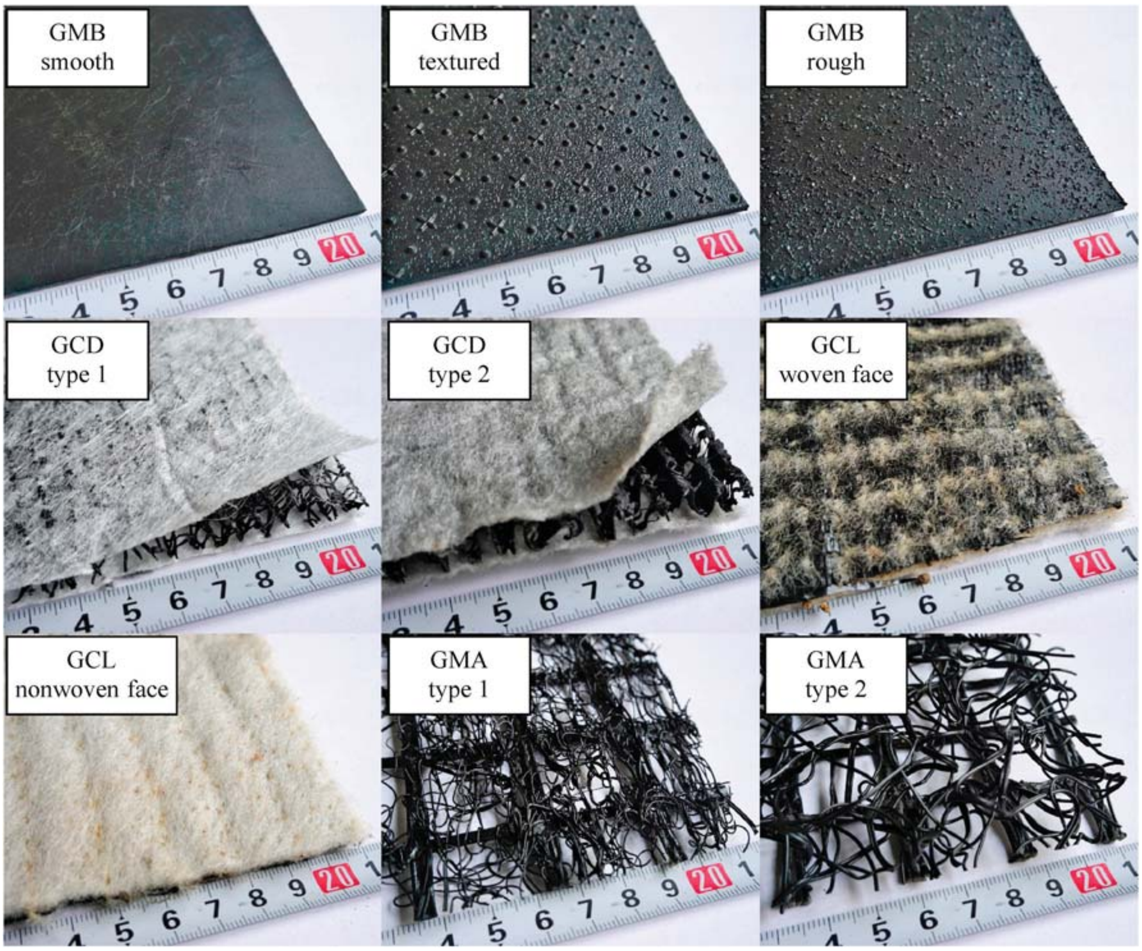

Fig. 1. Visual representation of the geosynthetics tested with scale reference (in cm).

and Özdüzgün, 2001; Reyes Ramirez and Gourc, 2003; Monteiro et al., 2013; Ferreira et al., 2016). The interest in this type of test, sometimes also called tilting table or ramp test, is highlighted by the wealth of knowledge on this topic that is available in the literature (Girard et al., 1990; Lopes et al., 2001; Ling et al., 2002; Palmeira et al., 2002; Briançon et al., 2002, 2011; Palmeira, 2009; Pitanga et al., 2009, 2011; Carbone et al., 2014, 2015; Pavanello et al., 2016, 2018a). These studies mainly investigated the influence of the experimental test conditions and the possibility of testing different types of interfaces, analysing the possible variations of the test apparatus, the procedure and the interpretation of the results.

The inclined plane test is also standardised in Europe for soil-geosynthetic interfaces by the EN ISO 12957-2 (2005). However, its application to geosynthetic-geosynthetic interfaces is not as simple, because, despite the simplicity of the geometrical and mechanical concepts, the complex behaviour of the polymeric materials entails the need for further research in order to improve the method of interpretation of the results, also considering the various kinematic conditions of the sliding motion (Gourc and Reyes Ramirez, 2004).

This paper focuses on the assessment of the friction between different geosynthetics by means of the inclined plane test, with the aim of presenting an organic collection of results on seven typical interfaces. The friction angle of the interface was evaluated according to three different procedures and the results were compared to highlight the variability and repeatability of the data, analysing also the influence of certain conditions, such as the wear level and the state of hydration.

2. Test materials and interfaces

The present study focuses on seven interfaces between different geosynthetics, which are widely used in environmental works. A first set of interfaces was represented by the contact between a geocomposite drain (GCD_1) and three types of high-density polyethylene (HDPE) geomembranes, characterised by three different surface finishing. More specifically, the tests were conducted on a smooth geomembrane (GMB_S), a textured geomembrane (GMB_T), having a regular pattern of embossed protrusions, and a rough or "sandy paper" geomembrane (GMB_R), whose surface was roughened by a random application of small particles (see also Fig. 1 for a visual representation). All the geomembranes tested were 2 mm thick and with mass per unit area of 2000 g/m^2. The geocomposite drain GCD_1 was formed, instead, by a draining body enclosed between two nonwoven geotextiles as separation, filtration and protection layers; it was 6.1 mm thick under a pressure of 2 kPa and a mass per unit area of 670 g/m^2.

Smooth geomembranes have been used for decades, covering a wide range of applications, while textured geomembranes are often chosen when a better compliance and interaction between the geosynthetic materials or between geosynthetics and soil is needed. However, there may be situations that require a reduced interface friction, for example, to avoid stressing the GMB, GCL and GCD layers, which do not have an intrinsic function of tensile strength.

Other than the three aforementioned interfaces, the contact between a geosynthetic clay liner (GCL) and another type of GCD, hereinafter referred to as GCD_2, was also examined. More in detail, the GCL was formed by two different geotextiles, a woven and a nonwoven, including a bentonite layer; the overall thickness was of 6 mm and the mass per

Table 1
Main properties of the geosynthetics tested.

Geosynthetic identification	Description	Thickness (mm)	Mass per unit area (kg/m^2)	Tensile strength (MD) (kN/m)	Strain at max strength (MD) (%)
GCD_1	Geocomposite drain, type 1	6.1	0.67	18	–
GCD_2	Geocomposite drain, type 2	7.2	0.74	18	–
GMB_S	Smooth geomembrane	2	2.00	64	800
GMB_T	Textured geomembrane	2	2.00	64	800
GMB_R	Rough geomembrane	2	2.00	64	800
GCL	Geosynthetic clay liner	6	4.30	11.5	<20
GMA_1	Geomat, type 1	7	0.52	90	10
GMA_2	Geomat, type 2	15	0.79	80	12

unit area was of 4300 g/m^2. The GCD_2 was similar to the GCD_1, but was 7.2 mm thick under a pressure of 2 kPa and the mass per unit area was 740 g/m^2. Given that the GCL was characterised by two different faces, research was conducted on both the contacts between the GCD_2 and the woven and the nonwoven faces.

Finally, the contacts between the GCD_2 and two different composites for soil reinforcement (GMA_1 and GMA_2) were also analysed.

The GMA_1 was made of a woven geogrid obtained from high tenacity polyester multifilament yarns, protected by a polymeric coating, which was characterised by an improved adherence obtained by a multifilament polyolefin three-dimensional mat that extruded on it. The mesh of the geogrid was 30 × 30 mm wide, the overall thickness was of 7 mm and the mass per unit area was of 520 g/m^2. The nominal tensile strengths were equals to 90 kN/m (MD) and to 35 kN/m (CMD).

The GMA_2 was another polypropylene geomat, coupled with a woven geogrid as reinforcement, made of a core of polyester yarns with a polymeric protective coating. The mesh of the geogrid was 25 × 25 mm wide, the overall thickness was of 15 mm and the mass per unit area was of 790 g/m^2. The nominal tensile strength in the longitudinal direction was equals to 80 kN/m. During tests, the geomats GMA_1 and GMA_2 were arranged, according to the operative conditions, with the geogrid directly in contact with the GCD and the mat on the other side. In this study, we didn't use filling soil for interfaces with GMAs, with the aim of analysing only the effects due to the geosynthetics in contact, which is also a conservative approach. The main properties of the geosynthetics examined are summarised in Table 1, while images, for a visual representation, are shown in Fig. 1. Finally, the various interfaces tested in the experimental programme are summarised in Table 2.

3. Test apparatus and procedure

The tests were conducted at the ICEA laboratory (University of Padova, Italy) using the inclined plane apparatus shown in Fig. 2. This device is typically composed of a tilting plane and of a block, which is movable and configured to slide along the inclined plane. One geosynthetic is fixed to the table while the second one is linked to the block; the test consists in studying the behaviour of the interface in terms of block displacements along the plane, while the inclination of the plane continuously increases at a constant speed. In this device the inclined plane had a length of 1.10 m and width of 0.25 m while the block presented a contact surface between geosynthetics with a length of 0.42 m and width of 0.21 m. During the tests, the lower side of the sliding block was fully covered by the geosynthetic specimen that was fixed on the front and back sides of the block. A straight sliding down motion was insured by two lateral guides, which also had the function of fixing the lower specimen to the plane, along the both sides, for the entire length. To avoid additional friction forces between the guides and the block, the latter was provided with four side wheels, parallel to the plane. Despite the solutions adopted in other testing devices, in this apparatus the side wheels did not act vertically but horizontally and they did not support the block. In this way, the weight of the block acted completely on the contact surface and there was no gap between geosynthetic and geosynthetic. Lastly, the inclination of the plane (β) could vary between 0° and about 45° at a constant speed of 3 ± 0.5°/min.

The test procedure adopted allowed the measurement of the friction angle according to three different modes (see below for details). The test started with the table in a horizontal configuration; the inclination of the table increased at a constant speed and the angle of inclination, β_0, at which the block started sliding, was checked. The static equilibrium at this stage involves that $\phi_0 = \beta_0$, where ϕ_0 is the angle of friction at "first movement".

It should be noted that interfaces can exhibit very different test behaviours (Gourc and Reyes Ramirez, 2004; Pavanello and Carrubba, 2016). For some interfaces β_0 can be easily identified because a fast sliding motion occurs upon exceeding this angle; in other interfaces, in contrast, the beginning of the motion is more difficult to detect because it occurs at a very slow pace; finally, in some other cases still a complex mode of sliding takes place with displacements that do not necessarily bring to an incipient failure. In this research, to overcome difficulties related to the block's kinematics, the angle of friction at first movement ϕ_0 was assumed to be equals to the β_0 angle of the inclination of the plane when the block performed a displacement of 1 mm, which is a conventional threshold value.

It is important to note that the standard EN ISO 12957-2 (2005) does not consider ϕ_0 a representative parameter and suggests continuing the test until the block displacement reaches the value of 50 mm. The inclination of the table reached at this stage, β_{50}, is assumed to be equals to the "standard" friction angle ($\phi_{stand} = \beta_{50}$) as defined hereafter and, for this reason, this approach is also indicated in the literature as "displacement procedure". Considering this measurement, it should be underlined that the displacement of 50 mm is rather arbitrary (perhaps established by analogy with the reference value of the direct shear test) and that the related ϕ_{stand} angle assumes a static equilibrium while the block is more properly in a kinematic condition, with velocity and acceleration that are not always negligible. In this condition, the mobilised interface friction should be more properly described by means of the

Table 2
Interfaces tested in the experimental programme.

Interface identification	Lower geosynthetic	Upper geosynthetic	Notation
a	Smooth geomembrane	Geocomposite drain, type 1	GMB_S - GCD_1
b	Textured geomembrane	Geocomposite drain, type 1	GMB_T - GCD_1
c	Rough geomembrane	Geocomposite drain, type 1	GMB_R - GCD_1
d	Geocomposite drain, type 2	Geosynthetic clay liner, woven face	GCD_2 - GCL_w
e	Geocomposite drain, type 2	Geosynthetic clay liner, nonwoven face	GCD_2 - GCL_{nw}
f	Geocomposite drain, type 1	Geomat, type 1	GCD_1 - GMA_1
g	Geocomposite drain, type 1	Geomat, type 2	GCD_1 - GMA_2

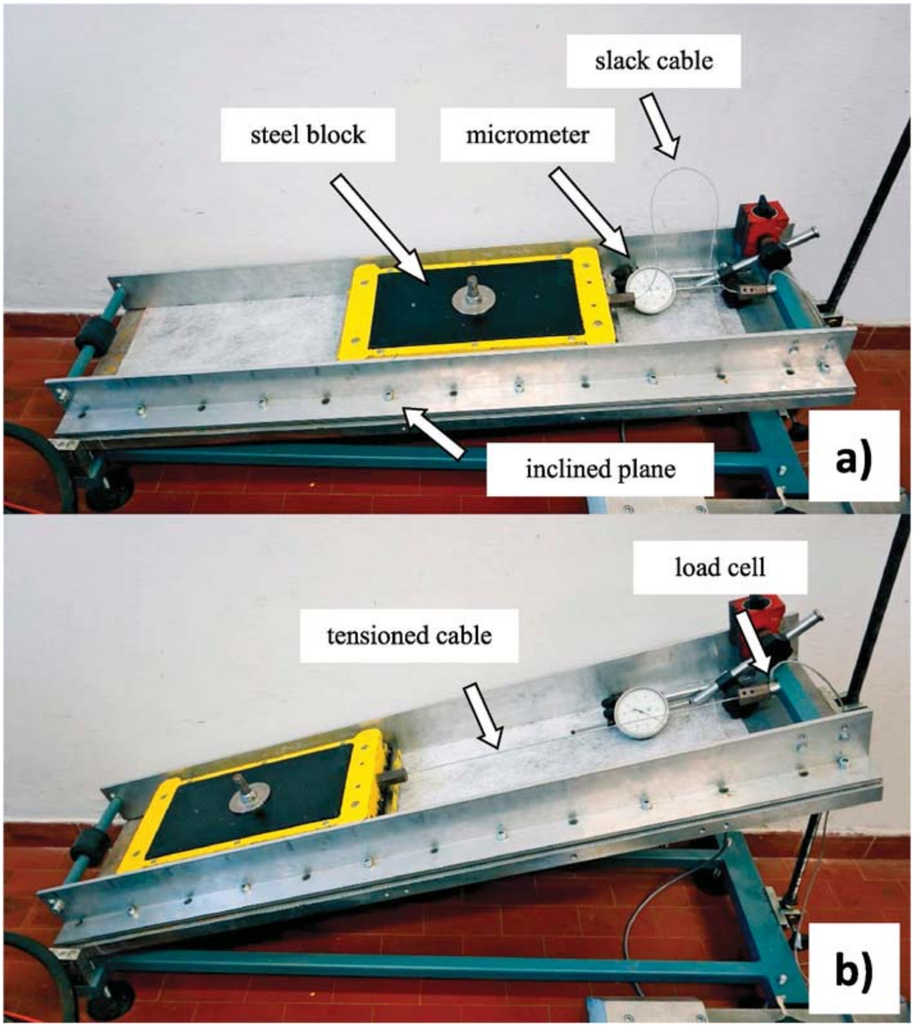

Fig. 2. Configuration of the inclined plane device (a) at the initial phase of the test and (b) during the force procedure.

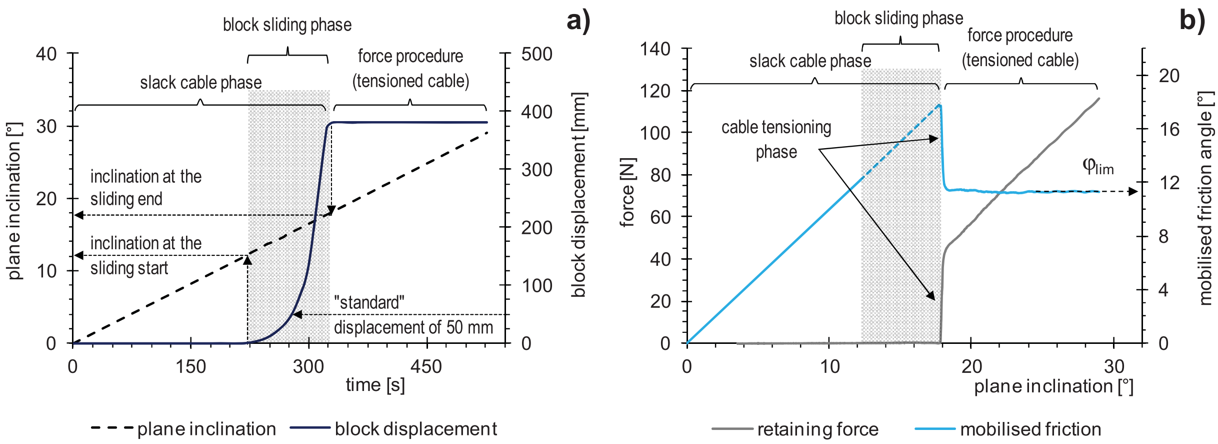

Fig. 3. Typical results of the "force procedure": (a) variation of plane inclination and block displacement as a function of time and (b) retaining force and mobilised friction angle as a function of plane inclination.

dynamic equilibrium equation along the plane direction:

$$g \sin \beta - g \cos \beta \tan \phi_{dyn} = a \quad (1)$$

where β is the plane inclination angle, a is the block acceleration, g is the gravity acceleration and ϕ_{dyn} is the dynamic friction angle. For this reason, the definition of the ϕ_{stand} angle is still a matter of scientific debate (Othmen and Bouassida, 2017).

As reported by Briançon et al. (2011) a further strength parameter should be evaluated at the end of the test by using the "force procedure". To this end, the block is linked to the inclined plane frame by a steel cable, which limits its displacement. Therefore, after the sliding, the

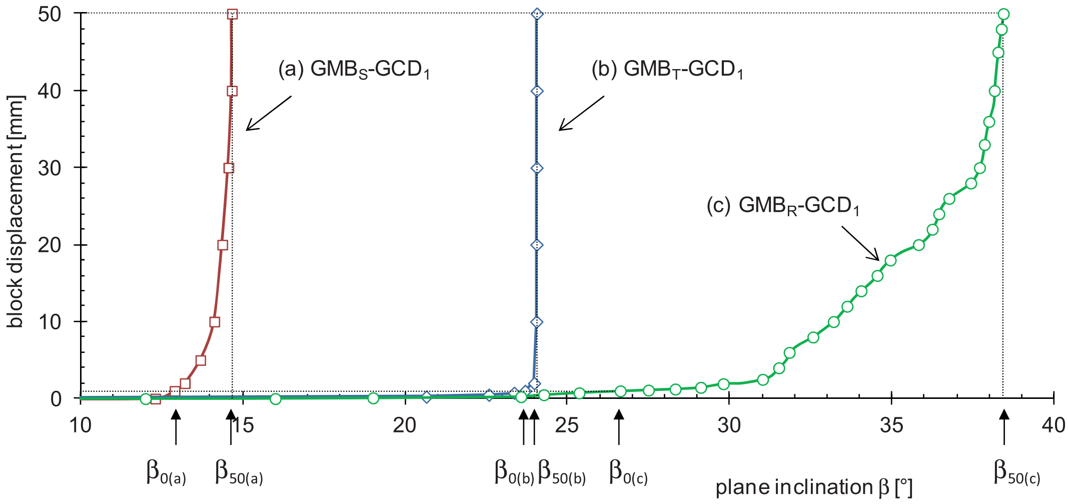

Fig. 4. Block displacement as a function of plane inclination for the interfaces between the geocomposite (GCD_1) and the three geomembranes (GMB_S, GMB_T, GMB_R) following the inclined plane test.

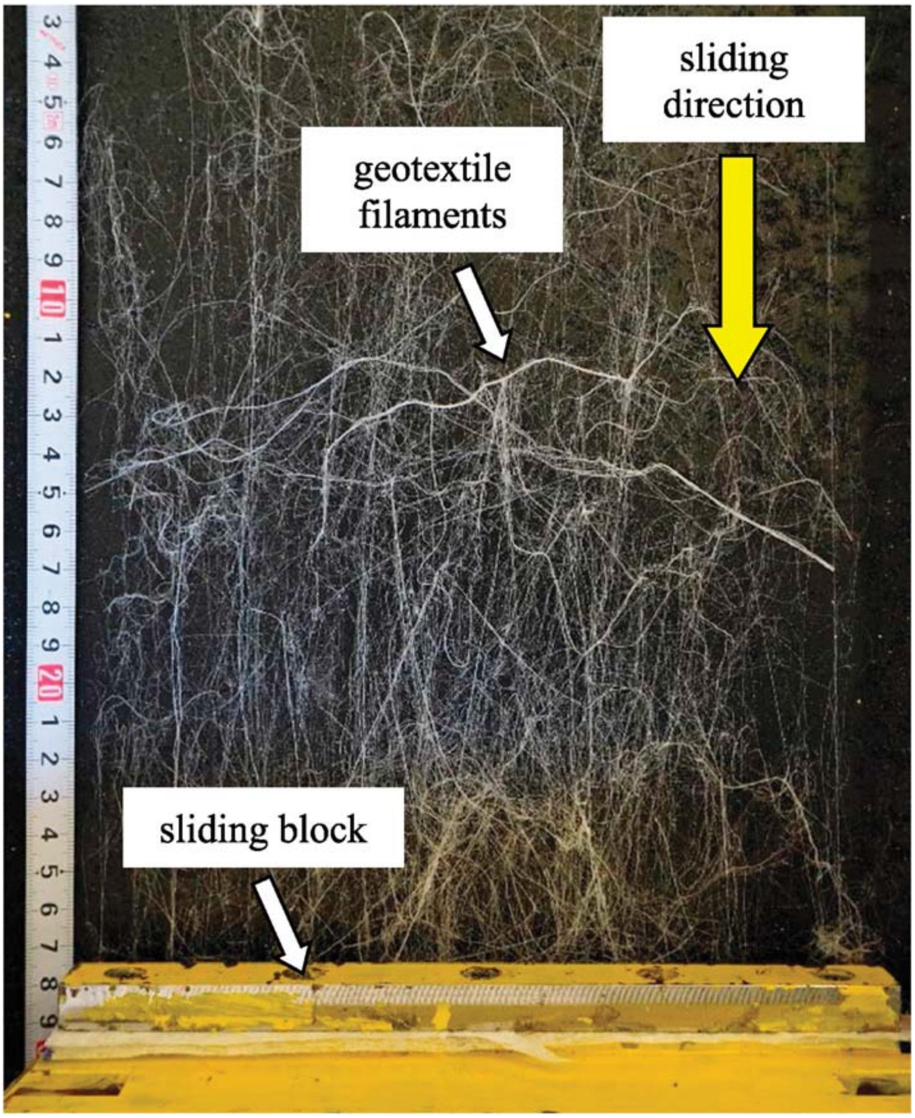

Fig. 5. Filaments of the nonwoven geotextile of the GCD_1 entangled with the asperities on the GMB_R surface after three sliding motions.

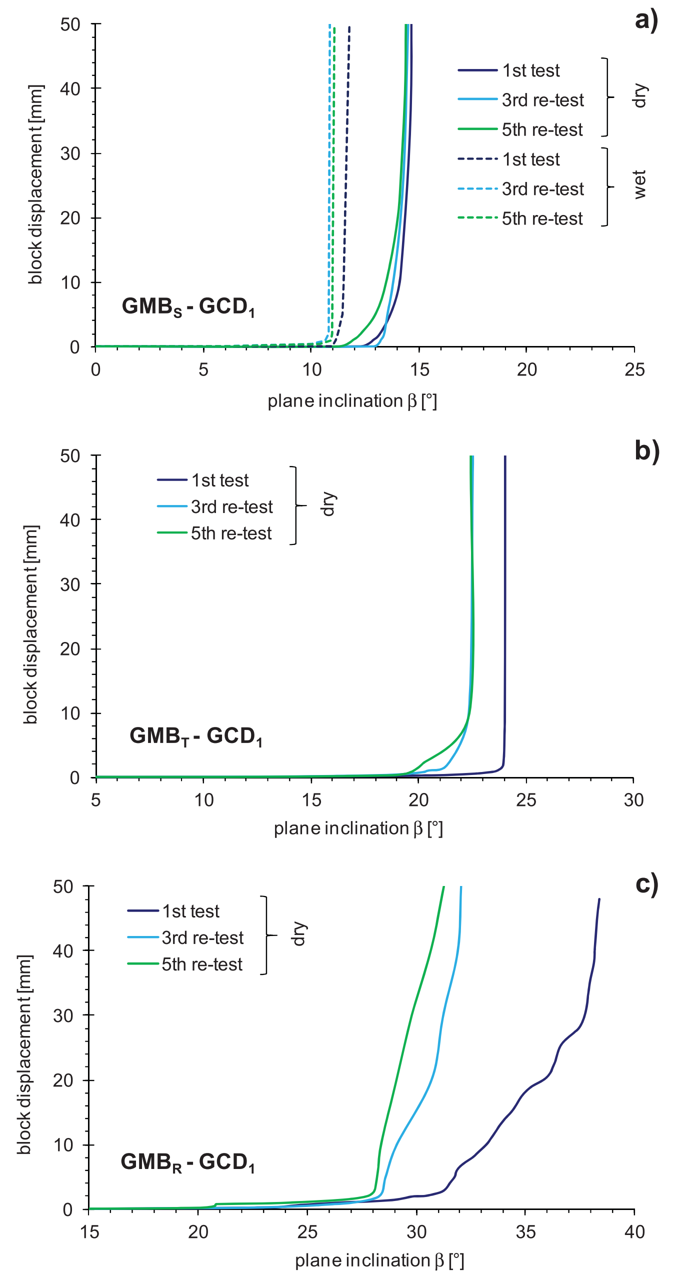

Fig. 6. The effect of wear on the inclination-displacement curves of the interfaces exposed to repeated tests: (a) GMB_S-GCD_1 for dry and wet conditions, (b) GMB_T-GCD_1 for dry conditions and (c) GMB_R-GCD_1 for dry conditions.

block is retained by the cable, which is parallel to the plane and linked to a load cell, able of measuring the tensile retaining force required to ensure the static equilibrium of the block (Fig. 2). During this phase of the test, a continuous measurement of the tensile force, F(β), is carried out while the plane continues to tilt at a constant speed (dβ/dt = 3.0°/min). The mobilised friction angle can be evaluated from the balance of forces as:

$$tan\phi = tan\beta - \frac{F(\beta)}{Wcos\beta} \quad (2)$$

where W is the weight of the block. Although the inclination angle of the table increases, the force F(β) increases in such a way that the mobilised friction remains almost constant (Briançon et al., 2011), so that a new parameter, called limit friction angle (ϕ_{lim}) in the present paper, can be defined. An example of a force procedure test is reported in Fig. 3. More specifically, the initial phase with a slack steel cable, the sliding of the block and the final phase with the tensioned cable are highlighted in Fig. 3a, while the corresponding development of the retaining force, as a function of the plane inclination, is shown in Fig. 3b. In Fig. 3b the mobilised friction, evaluated according to eq. (2), is also plotted. It should be noted that the value provided by this equation in the first phase, when the cable is slack, corresponds to the correct mobilised friction angle only if the motion develops with a negligible acceleration (indeed, for F = 0, ϕ = β). Otherwise, in the sliding phase the sliding friction should be evaluated by means of the dynamic equilibrium (eq. (1)), being ϕ ≠ β. Due to this uncertainty, the portion of the curve of the mobilised friction, corresponding to the sliding phase, is shown in Fig. 3 with the dashed line instead of a continuous one. Only the part of the curve related to the tensioned cable stage, which is the only one useful, will be reported hereinafter.

In the inclined plane apparatus adopted, the weight of the block fully acts on the geosynthetic interface and the vertical stress, σ_{v0}, is applied by means of steel plates placed inside the block. It should be noted that the average normal stress, σ_{va}, decreases as the plane inclination angle β increases ($\sigma_{va} = \sigma_{v0} \cdot cos\beta$) and that a trapezoidal normal stress distribution occurs along the interface length, rather than a uniform one, according to the block centre-mass height and to the block length. This is an issue common to all inclined plane devices (Palmeira et al., 2002) but, for the adopted geometries, this effect does not entail an excessive variation of normal stress; more specifically, the maximum variation of the normal pressure, at the front and back borders of the contact area, compared to the mean value, was of ±8% for β = 10°, ±17% for β = 20° and ±26% for β = 30°. Research conducted by authors on the effect of the non-uniform distribution of normal stress, as regards the interface friction mobilisation, is under way although preliminary results have already shown that it is not very significant, even for moderated inclinations (up to about 25°–30°).

The measurements, during a test, include time, plane inclination angle, block displacement and, during the “force procedure”, the force required to restrain the block.

All tests were carried out at a vertical stress of 5 kPa and at a laboratory temperature ranging from 20° to 24 °C. For all the interfaces studied at least three different couples of specimens were tested to outline the possible range of variability of the friction parameters, which for some materials has a greater dispersion, for others less. A first measurement provided ϕ_0 and ϕ_{stand} of virgin specimens. After a displacement of about 0.3 m also ϕ_{lim} was measured for the first time.

To investigate the surface damage, due to the mutual sliding, the tests were repeated at least 5 times on each couple of specimens; after each test, the plane was lowered and the block was placed in the starting position in order to allow the block to slide again on the same contact area, thus obtaining friction parameters related to the amount of the displacement cumulated.

Finally, both dry and wet conditions were investigated for some interfaces: in this respect, it should be underlined that an interface’s state of hydraulic saturation is very difficult to generate on an inclined plane device (some attempts can be found in Briançon et al., 2002). For this reason, wet tests were conducted, only for comparative purposes, by immersing the specimens in demineralised water for a certain amount of time (about 1 h for the GCD and 15 h in the case of the GCL). Once the specimens were extracted from the water, they were left to drain the water excess for a few seconds, then mounted on the device and tested.

4. Test results

4.1. Interfaces involving the geomembranes (GMB_S, GMB_T, GMB_R)

The block displacements as a function of plane inclination of the three interfaces between the HDPE geomembranes and the drainage geocomposite GCD_1, in dry conditions and following the inclined plane test, are depicted in Fig. 4. As the results show, the behaviour of the

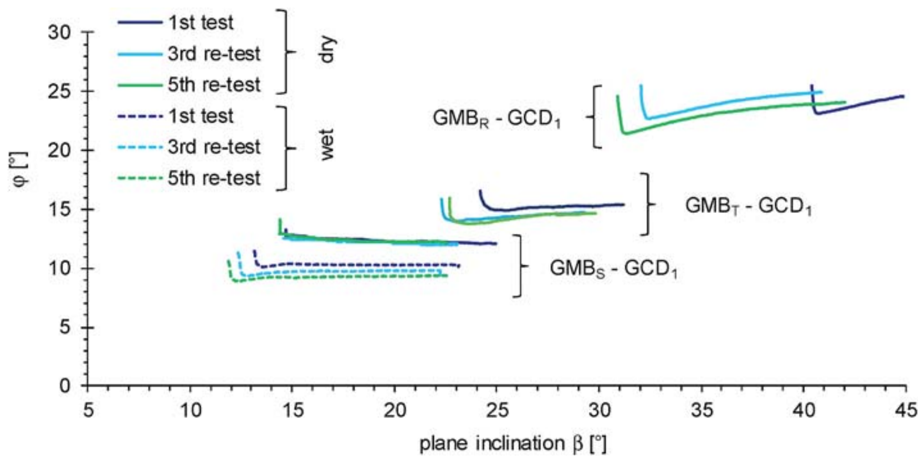

Fig. 7. The results of the force procedure for the interfaces involving the geocomposite drain (GCD) and the three types of geomembranes following repeated tests.

interfaces changed significantly depending on the type of geomembrane tested, suggesting that the geomembrane surface finish had a significant role on the response of the interface as a whole. The behaviour of geocomposite (GCD_1) - smooth geomembrane (GMB_S) interface is an example of "gradual" sliding type behaviour in that the block performed a progressive slide along the inclined plane at a very low speed. The acceleration of the block was thus negligible and there was a certain time lapse from when the block reached a displacement of 1 mm and when it reached the corresponding displacement of 50 mm. As a consequence, also the angle of inclination β_0 was different to β_{50} or, in other terms, the shear strength angle ϕ_0 was significantly lower than ϕ_{stand}.

The geocomposite (GCD_1) - textured geomembrane (GMB_T) interface displayed, instead, a different behaviour with a "sudden" sliding type motion, characterised by a marked acceleration. Consequently, the time lapse between the displacements of 1 mm and of 50 mm was very short, so that the shear strength angles ϕ_0 and ϕ_{stand} were very similar. Even if in this case the acceleration of the block was not negligible, the ϕ_{stand} value could still be considered a useful reference for design purposes.

Finally, the geocomposite (GCD_1) - rough geomembrane (GMB_R) interface revealed yet another behaviour, which was very complex and here referred to as "uneven" sliding. Small displacements occurred at low inclination angles, which were not indicative of an incipient sliding, but rather connected to the stretching of the GCD fibre and, for this reason, the shear strength angle ϕ_0 was not significant in this type of interface. However, at high inclination angles, the displacements increased in an irregular way so that the maximum shear strength of the interface was very difficult to define because significant displacements, which were sometimes greater than 50 mm, were observed without an inexorable motion beginning.

A visual observation of the surfaces at the end of the tests, in the case of the GMB_T-GCD_1 and GMB_R-GCD_1 interfaces, showed that no punching effect, by the geomembrane spikes, occurred since tests were performed in conditions of low normal stress; in the case of the GMB_R-GCD_1 interface, in particular, the interaction between the geotextile and the geomembrane surfaces consisted mostly in the interlocking mechanism between the filaments of the geotextile and the geomembrane roughness. This phenomenon, reported in the literature as "hook and loop" effect (Hebeler et al., 2005), is known to be responsible for the uneven sliding motion, given that the irregularities of the block motion are attributable to the random tearing of filaments that are caught by the geomembrane asperities (Fig. 5). Interestingly, despite the very different behaviour of the GMB_T-GCD_1 and GMB_R-GCD_1 interfaces, the block displacement was observed to start at comparable plane inclinations; in other terms, while the values of ϕ_{stand} of the two interfaces was very different, the corresponding values of ϕ_0 were comparable, as if the interaction with the fibres had little influence on ϕ_0.

The behaviour of the interfaces, as reported in Fig. 4, referred to dry virgin specimens, i.e. specimens that had not experienced any previous relative displacement. To complicate matters further, the behaviour of interfaces also depends on the wear level and on the state of hydration, as is shown in Fig. 6. In the figure are depicted the inclination-displacement curves of a same pair of specimens, exposed to repeated tests, i.e. at the beginning of the test (1st test, virgin condition), at the third repetition of the test (3rd re-test following a cumulated displacement of about 0.7 m) and at the fifth repetition (5th re-test following a cumulated displacement of about 1.4 m).

In dry conditions, the GMB_S-GCD_1 interface (Fig. 6a) continued to display a gradual sliding type behaviour even with increasing wear, while in wet conditions it revealed a sudden sliding type motion.

Regarding the GMB_T-GCD_1 interface (Fig. 6b), the virgin specimens displayed a sudden sliding movement, which tended to become more similar to the gradual one as the relative displacement experienced by the interface increased. A significant reduction of the friction angle, passing from the first to the third test repetition, was also observed in this case while the shear strength was more stable in the subsequent tests.

Finally, in the case of the GMB_R-GCD_1 interface (Fig. 6c), the sliding behaviour gradually tended to become more regular with an increase in wear, while the reduction of interface friction with the displacement level also occurred following the third repetition of the test.

Regarding the force procedure, the mobilised friction angle as a function of plane inclination was also compared in a pair of specimens of each interface, which were again exposed to the same hydration conditions and repeated tests, as previously described (Fig. 7).

A premise to be made is that this test method allows to obtain measurements of the mobilised friction only for plane inclination angles greater than the static value. If this aspect is not a problem in most cases, it becomes a limit when the interface is characterised by high static friction values, such as in the case of the GMB_R-GCD_1 interface, whose virgin specimens reached friction angles of the order of 40°. In this case, indeed, the evaluation of the mobilised friction can be done only in a narrow range of inclinations, limited to the upper side by the maximum inclination that was reachable by the device, which was in the order of about 45°. Besides, this upper value is not only a simple mechanical limit, which could be easily overcome, since it makes no sense to lead the test to higher inclinations, for which the eccentricity of the load can play a role that is no longer negligible. Fig. 7 shows that the mobilised friction in the GMB_S-GCD_1 and GMB_T-GCD_1 interfaces remained sufficiently constant, allowing an easy definition of the value of ϕ_{lim}, whereas, in the case of the GMB_R-GCD_1 interface, the values tended to increase proportionally to the inclination of the plane. In the latter case,

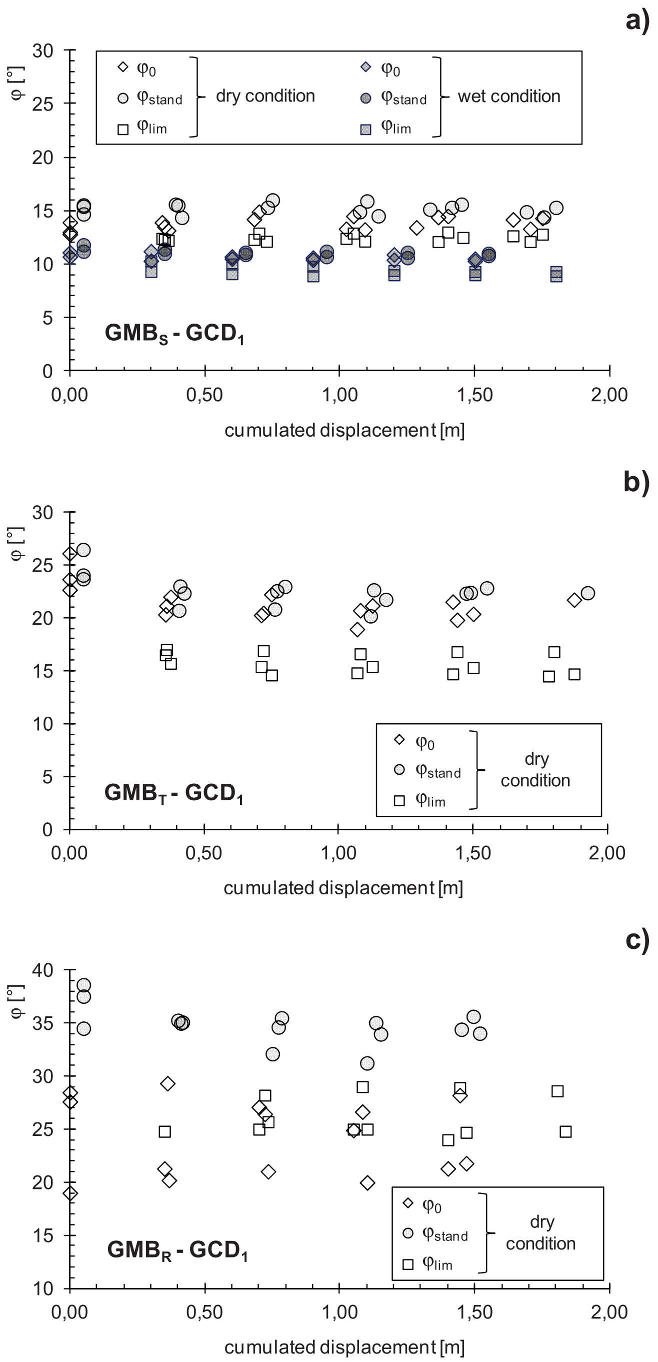

Fig. 8. Shear strength angles as a function of cumulated displacement for the three types of interfaces following repeated tests: (a) GMB_S-GCD_1 for dry and wet conditions, (b) GMB_T-GCD_1 for dry conditions and (c) GMB_R-GCD_1 for dry conditions.

the authors chose to evaluate the ϕ_{lim} angle referring to the last section of the curve. Finally, a graphical summary of the data as a function of the cumulated displacement completes the presentation of the experimental results (Fig. 8).

This representation allows to evaluate the repeatability of the tests, in terms of data scattering, as well as the overall influence of the wearing process on the shear strength available. The interface GMB_S-GCD_1 (Fig. 8a) showed a difference of some degree between ϕ_0 and ϕ_{stand}, while the force procedure presented the lowest values, roughly 3° lower than the standard value. As expected, the wear of the surfaces, due to repeated tests, did not significantly change the angle of shear strength.

The second interface, GMB_T-GCD_1, showed values of ϕ_0 and ϕ_{stand} that were almost coincident for the second and third test repetition (Fig. 8b), with a data scattering that was slightly greater than the previous case; moreover, the values of ϕ_0 and ϕ_{lim} were significantly different, with a gap of about 5°. The values of ϕ_0 and ϕ_{stand} decreased quickly with the increase in wear, passing from average values of about 24°, for virgin specimens, to average values of about 21°, following displacements in the order of 1.0 m.

Fig. 8c shows the results for the interface GMB_R-GCD_1; the mean values of ϕ_0 were slightly greater than those of ϕ_{lim}, while the values of ϕ_{stand} were remarkable greater. The data scattering was also noticeable, especially concerning the ϕ_0 values; in other words, the results repeatability for this interface was lower than in the previous two cases, due to the random interactions, with interlocking effects, between the fibres of the geotextile and the asperities of the geomembrane.

Finally, the distribution of shear strength in relation to the cumulated displacement showed a reduction of the ϕ_{stand} values of about 5°, passing from virgin to worn specimens and, therefore, the wearing effect was not negligible. Concluding, for all the three interfaces examined, the ϕ_{lim} values were those less sensitive to wear and the data scattering, related to the various surface finishing, may be a substantial parameter.

4.2. *Interfaces involving the geosynthetic clay liner (GCL)*

Referring to the two interfaces involving the GLC, some typical inclination-displacement curves are reported in Fig. 9, for repeated tests on a different pair of specimens for each side of the GCL, the woven (GCL_w) and the nonwoven (GCL_{nw}) interface. More specifically, Fig. 9a shows the sliding behaviour of the GCD_2-GCL_w interface in dry and wet conditions, while Fig. 9b depicts the sliding behaviour of the GCD_2-GCL_{nw} interface in dry conditions. As the figure reveals, the behaviour of both interfaces in dry conditions was quite similar and did not change significantly, passing from the nonwoven to the woven face. In both cases the motion was gradual and the shear strength proportionally increased with the cumulated displacement experienced by the interface, as highlighted by the repetition of tests. In contrast, when passing from the dry to the wet condition, which was evaluated for the woven face alone, the sliding motion changed from gradual to sudden (Fig. 9a). Moreover, in the wet conditions the wear effect also induced a reduction of the interface friction available. This may be due to a different interaction between the fibres of the two geosynthetics and to a minimal leakage of bentonite from the GCL, which can dirty the sliding surface.

Regarding the force procedure, the mobilised friction angle as a function of plane inclination was again compared in the same pair of specimens in contact with each face, the woven (Fig. 10a) and nonwoven (Fig. 10b) face, which were again exposed to the same hydration conditions and repeated tests, as previously described. After an initial phase, in which the mobilised friction increased proportionally to the increase in inclination, the curves had a tendency to stabilise at a later phase, leading to reasonably assume ϕ_{lim} equals to the maximum values reached. It is interesting to observe how the curves provided by the force procedure shows a lower variation, on repeating the tests, than that related to the standard procedure (Fig. 9).

Finally, Fig. 11 shows a summary of the experimental results, for both GCL faces, as a function of the cumulated displacement. Regarding the contact on the woven face (Fig. 11a), all the friction parameters showed a clear reduction, passing from dry to wet conditions, corresponding to roughly 5°–6°, for ϕ_0 and for ϕ_{lim}, and to 7°–10° for ϕ_{stand}. In line with the "gradual" sliding behaviour, ϕ_{stand} was always appreciably greater than ϕ_0 in dry conditions, while the two angles were quite coincident in wet conditions, due to the "sudden" sliding motion. Furthermore, ϕ_{lim} was always lower than ϕ_0 and ϕ_{stand}; the difference between ϕ_{stand} and ϕ_{lim} was of about 7° in dry conditions and of about 4° in wet conditions. The data scattering was greatest for ϕ_0 in dry conditions (about 5°) and lowest for ϕ_{lim}, in both dry and wet conditions; in the latter case the dispersion did not exceed 1°. All the friction

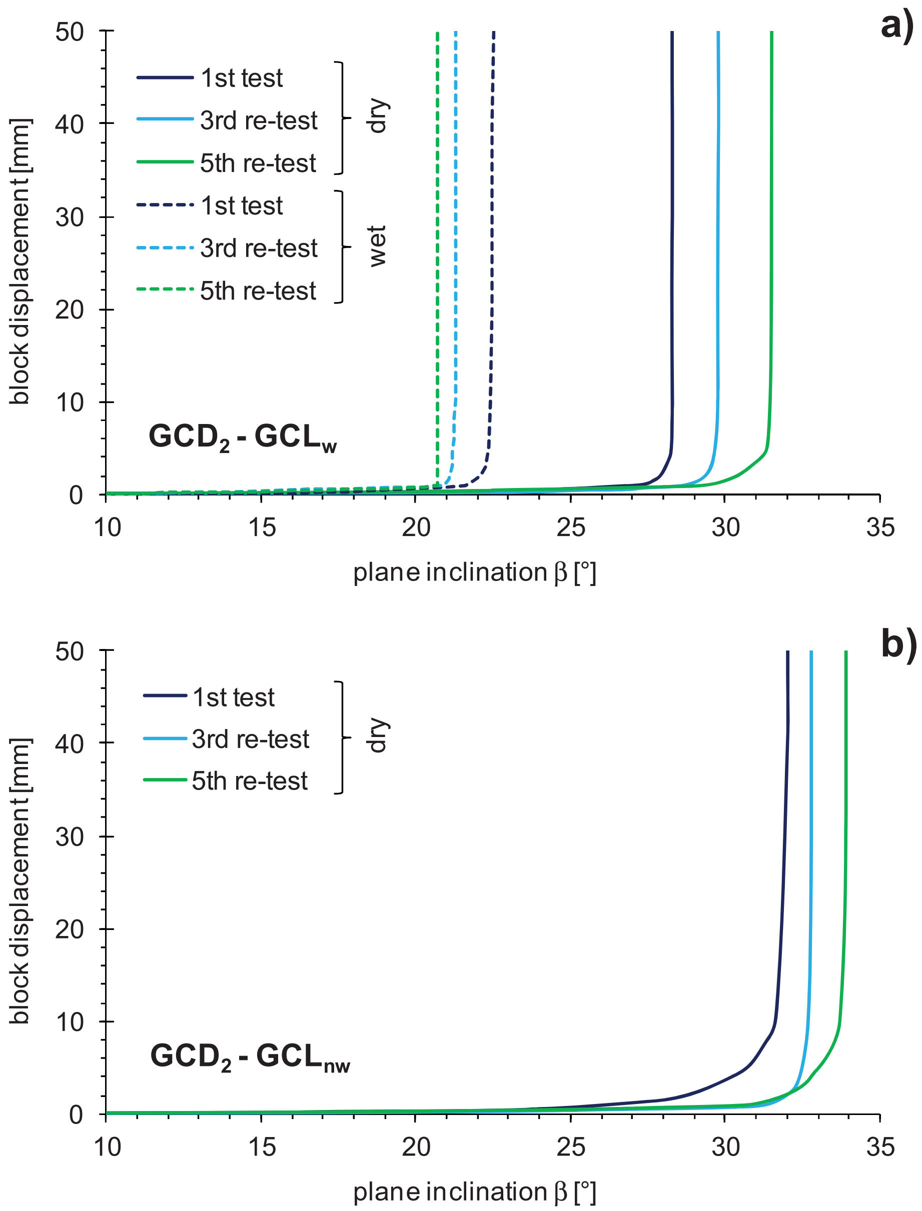

Fig. 9. The effect of wear on the inclination-displacement curves of the two GCL interfaces exposed to repeated tests: (a) GCD_2-GCL_w for dry and wet conditions and (b) GCD_2-GCL_{nw} for dry conditions.

parameters showed a moderate dependence from the cumulated displacements with a tendency to increase in dry conditions and to reduce in wet conditions.

The friction parameters showed similar results in the case of the contact on the nonwoven face, exposed to dry conditions (Fig. 11b). Also in this case the sliding behaviour was gradual and the ϕ_{stand} values were considerably greater than those of ϕ_0, with decreasing differences as the wearing increased. However, both ϕ_0 and ϕ_{stand} values increased proportionally, up to about 4°, with the increase in cumulated displacement. In contrast, the values of ϕ_{lim} were the lowest and they remained almost constant independently of the variation in cumulated displacement. Finally, when comparing Fig. 11a and b, the friction values, which were mobilised in dry conditions by the woven and nonwoven faces of the GCL, were quite similar, with slightly higher values in the latter case.

4.3. Interfaces involving the two types of geomats (GMA_1, GMA_2)

The two interfaces involving the GMAs showed a similar behaviour during the tests; as highlighted by the inclination-displacement curves both the GCD_1-GMA_1 and the GCD_1-GMA_2 interfaces, in dry conditions, exhibited a gradual sliding motion that did not change significantly even when the tests were repeated (Fig. 12).

The corresponding curves of the force procedure are reported in Fig. 13, while the summary of the experimental results is shown in Fig. 14.

For both interfaces, the values of ϕ_0 were clearly lower than those of ϕ_{stand}, due to the gradual sliding behaviour of the interface (Fig. 14). The difference was of about 3° for the GCD_1-GMA_1 interface and of about 4°–5° for the GCD_1-GMA_2 and it appeared to be unrelated to the cumulated displacement. In both cases the data scattering of the ϕ_0 parameter was relevant, being more significant for the GCD_1-GMA_2 interface. Finally, the values of ϕ_{lim} were slightly lower than those of ϕ_0 for the GCD_1-GMA_1, while they were similar for the GCD_1-GMA_2 interface.

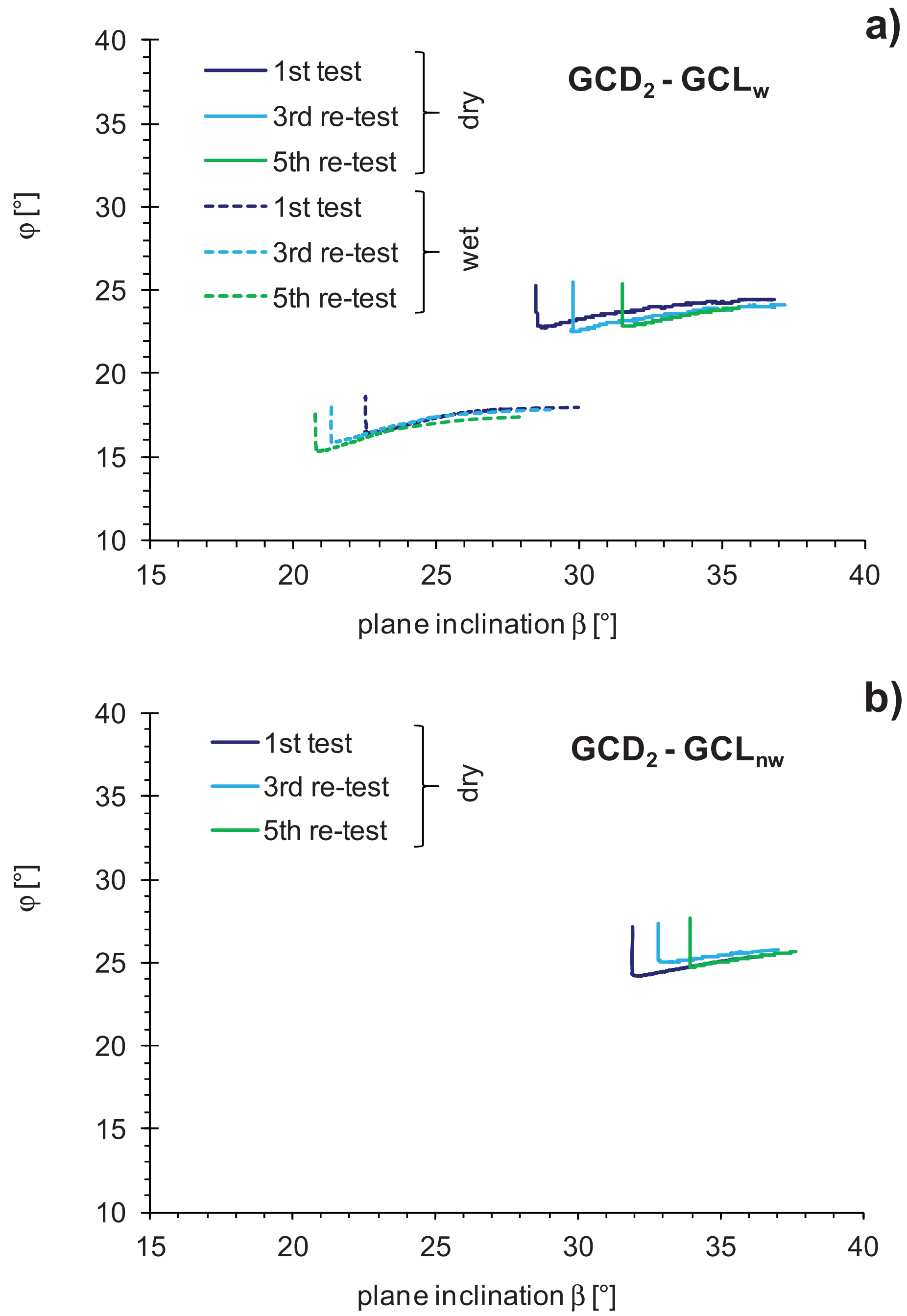

Fig. 10. The results of the force procedure for the two types of GCL interfaces following repeated tests, (a) GCD_2-GCL_w for dry and wet conditions and (b) GCD_2-GCL_{nw} for dry conditions.

5. Discussion

5.1. Some considerations about the choice of the shear strength parameter

The results reported in the previous paragraphs highlight the different behaviours that the interfaces between geosynthetics can display during an inclined plane test.

One aspect of these tests, which has not fully been cleared yet, is connected to defining which is the most suitable shear strength parameter for the characterisation of each interface. Unfortunately, given the variability of the possible behaviours, a univocal criterion, that is applicable in all cases, is difficult to achieve. Indeed, in the sudden sliding behaviour, for example, being the motion sudden and fast, the mobilised friction during the sliding phase should be evaluated by means of eq. (1), as previously described. This equation gives values of $\phi < \beta$ for $a > 0$, while $\phi = \beta$ for $a = 0$. Consequently, the correct interpretation of this type of test would be like that showed in Fig. 15 and relative to the GMB_T-GCD_1 interface. More specifically, in Fig. 15a the development of the block displacement and speed together with the plane inclination are graphed as a function of time, while in Fig. 15b the mobilised friction angle, as deduced from eq. (1), as well as the speed of the block are depicted in relation to its displacement. This interpretation allows to identify a clear separation between the static and dynamic condition, being the latter characterised by a speed, which is not negligible, and by a dynamic friction value that is lower than the static one. It should be noted that, given the rapidity with which the sliding motion develops, the plane inclination is, in fact, constant during this phase and, therefore, the "standard" interpretation of the test, which

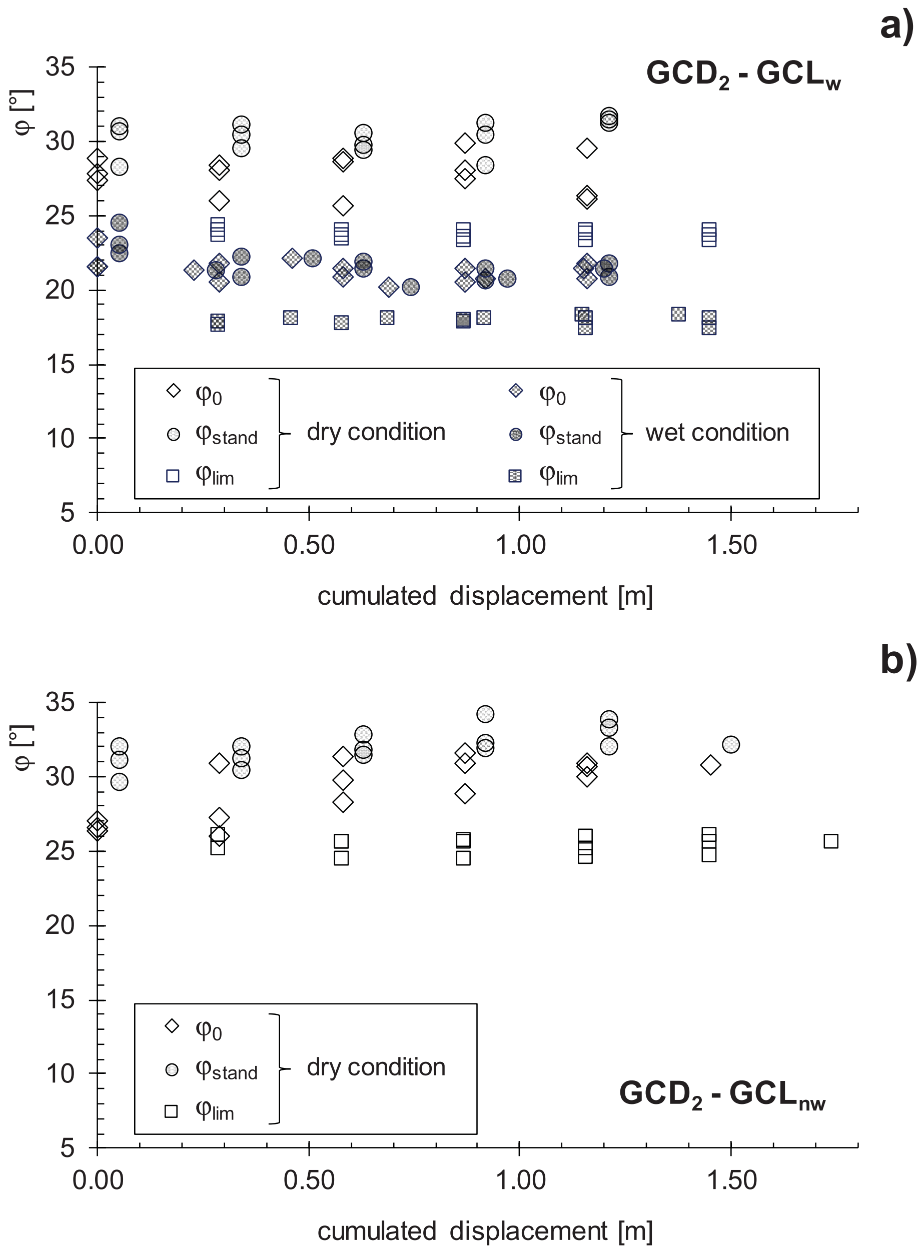

Fig. 11. Shear strength angles as a function of cumulated displacement for the two types of GCL interfaces following repeated tests: (a) GCD_2-GCL_w for dry and wet conditions and (b) GCD_2-GCL_{nw} for dry conditions.

neglects the effect of acceleration, is equivalent to considering the angle of friction constant during sliding. However, the value ϕ_{stand} correctly captures the value of static peak friction and also the value ϕ_0, which is very close to it, could be taken as a useful and slightly more conservative parameter. Finally, it may be useful to observe that the drop of the friction available following the peak (Fig. 15b) is not associated with a post-peak condition, but rather to the transition from a static to a dynamic phase and, therefore, to the transition from a static to a sliding friction. As shown by several works carried out by means of the direct shear test (Jones and Dixon, 1998; Hebeler et al., 2005; Bacas et al., 2011, 2015), in conditions of low normal stress the peak and the post-peak shear strength tend to be similar, in contrast to what would happen at medium-high normal stress. In this perspective, the fact that the inclined plane test allows to evaluate the peak friction angle must not be considered a limiting factor for design purposes in static conditions. On the contrary, the evaluation of the sliding friction, together with the static one, could be effectively useful if a dynamic condition should occur, such as that induced by an earthquake.

Fig. 16 depicts, instead, the graphics of an inclined plane test conducted on an interface characterised by a gradual sliding behaviour, such as that occurring in the case of the GCD_1-GMA_1 interface. The transition between the static and kinematic condition is not so clear-cut, in this case, the block's speed is always very low and the acceleration values are practically negligible. As a consequence, eq. (1) indicates that the values of the dynamic friction angle are equals to the inclination of the plane, even in conditions of motion. A sudden drop of the interface friction, passing from the static to the kinematic condition, is not observed but rather a gradual build-up; the interface responds to the increase in shear stress, due to the increase of the plane inclination, with a proportional increase of the mobilised sliding friction, at the expense of a slight increase of the sliding speed.

Thus, a relationship between sliding friction and speed takes place, as already previously reported (Pavanello et al., 2018b, c). In conclusion, for interfaces exhibiting this behaviour, the ϕ_{stand} is a friction angle

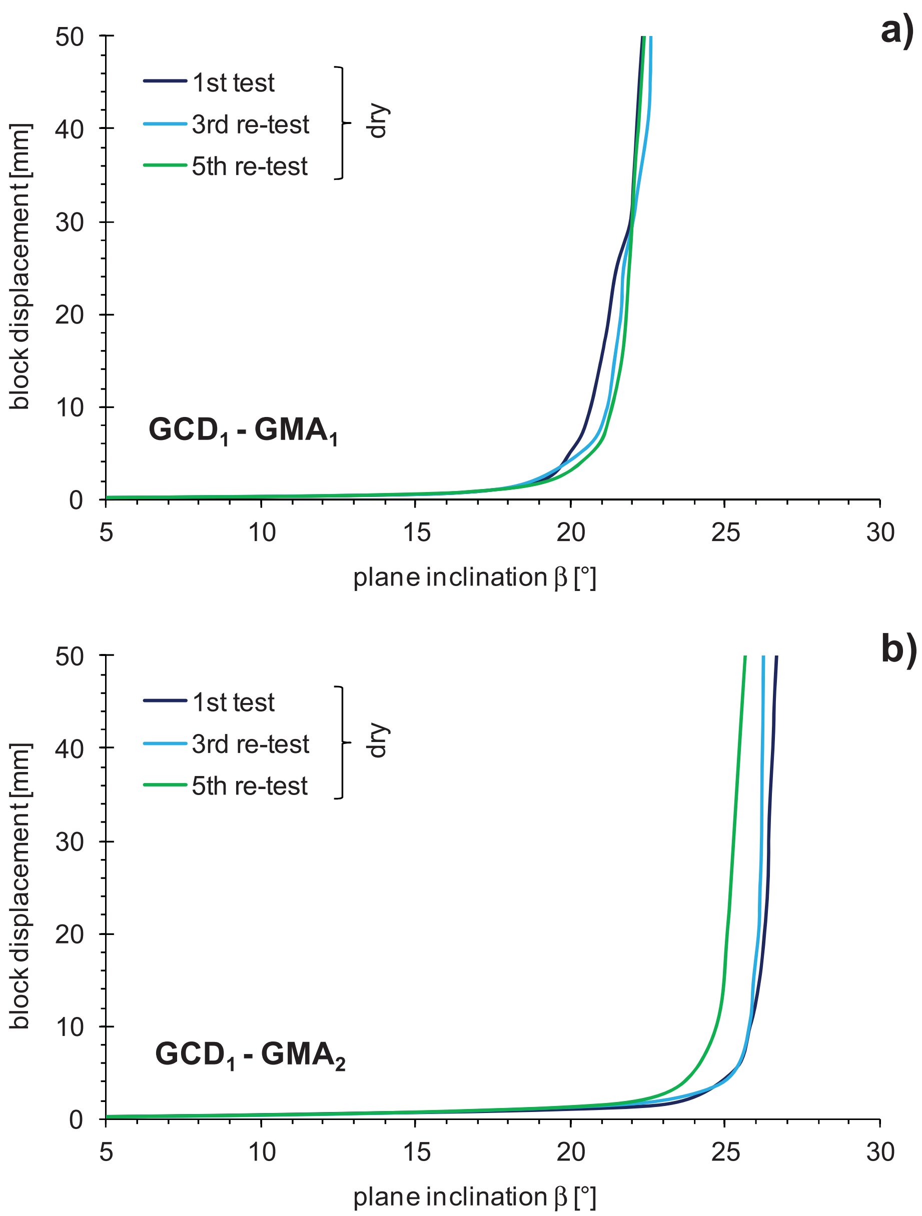

Fig. 12. The effect of wear in dry conditions on the inclination-displacement curves of the two GMA interfaces, the (a) GCD_1-GMA_1 and the (b) GCD_1-GMA_2, exposed to repeated tests.

value that the interface mobilises only in a non-static condition, given that it is associated with a speed value, which, although small, does not allow to consider this state as static proper. Thus, the selection of a friction angle equals to ϕ_0 allows to go back to a condition that is associated to a sliding speed that, however apparently negligible, does not guarantee the associated state to be truly static.

In this respect, the result of the test, as shown in Fig. 17, is emblematic. In this case, a typical inclined plane test, performed again on the GCD_1-GMA_1 interface, was interrupted when a displacement of 1 mm was reached, at the end of which the displacement of the block was monitored by keeping the inclination of the plane on the value reached at that moment. The results show that, even for an inclination of the plane equals to β_0, the block slowly continued its motion, until reaching and exceeding the reference value of 50 mm. Thus, it remains to be established as to which value should the correct shear strength be referred to in these cases.

Regarding the evaluation of ϕ_0, it should be stressed that, for a block displacement of only 1 mm, it may be difficult to distinguish between a sliding at the interface and any displacements related to the shear deformation of the geosynthetics specimens. For this reason, it is extremely important to take care of how the material is fixed to the supporting surfaces, especially in the case of geocomposites characterised by a sandwich structure, which are not very stiff in the tangential direction. If the deformation of the specimens induced by the block weight cannot be considered negligible, the displacement measurement method should be improved or the reference value of 1 mm should be redefined.

In summary, the main problem related to gradual sliding interfaces, which has also been highlighted in another recent work (Stoltz et al., 2020), is that these contact surfaces do not show a clear transition between the static and kinematic condition. Indeed, the kinematic condition borders at the bottom with extremely slow motions, up to reaching conditions that could be confused with a sort of "creep". In this context, the only viable path seems that of monitoring the displacement of the block for a sufficiently long period to detect these very slow motions. This approach, however, may clash with other experimental difficulties due to the viscous behaviour of polymers, such as the possible deformability of the lower geosynthetic, which, under the action of normal

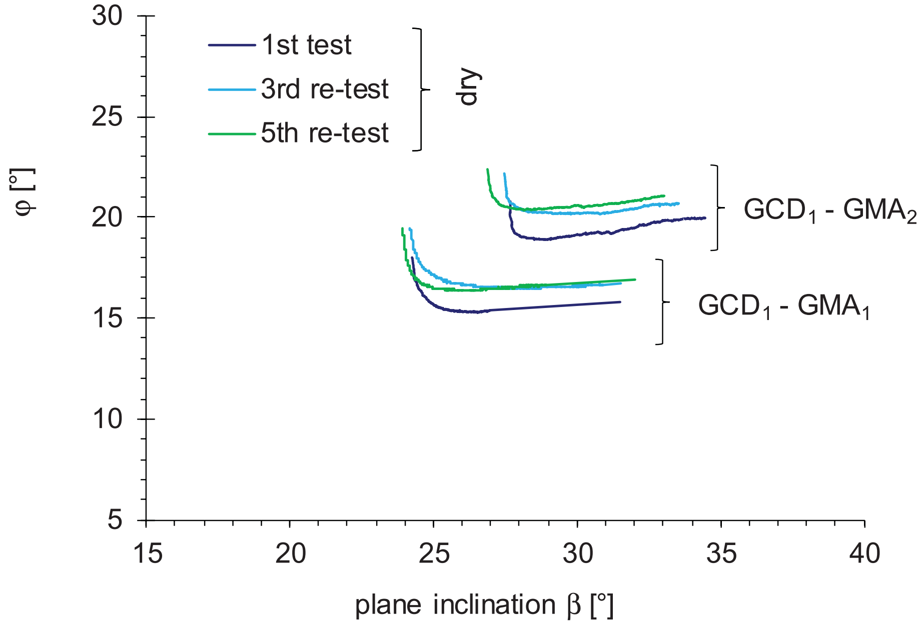

Fig. 13. The results of the force procedure for the two types of GMA interfaces exposed to dry conditions and following repeated tests.

stress, could create a sort of hollow, or other chemical-physical interaction, phenomenon which may lead to an apparent adhesion. In light of the above and despite the limits already highlighted, for these interfaces the parameter ϕ_0, although not associated with a completely static condition, may be considered a reference parameter, which is easily identifiable and useful even for a design approach if used with a well considered safety factor, which should be greater than that adopted in other cases, in order to take these very slow movements into consideration.

In addition to the gradual and sudden sliding motion, another behaviour, which has been reported to occur, is that of "stick-slip" type, characterised by a jerky movement (Gourc and Reyes Ramirez, 2004). None of the interfaces tested in this paper displayed this behaviour. We rather observed, instead, a further sliding motion, which we described as "uneven sliding behaviour", and that has hardly been mentioned in previous studies, to the best of our knowledge. This type of behaviour was exhibited, for example, by the GMB_R-GCD_1 interface. Based on a first brief analysis of the displacement-inclination curves, this behaviour could also be ascribed, at a first glance, to a kind of gradual sliding. However, the physical phenomenon that occurs in these cases is very different, given that the progression of the motion of the block does not seem to be related to a development of the sliding friction with speed but rather to a complex interaction of the fibres with the roughness of the geomembrane. An important consequence of this peculiar uneven sliding behaviour is that, for this interface, the first small displacements, such as those in the order of 1 mm, are not related to a condition of irreversible motion, as instead occurs in the gradual sliding behaviour. On the contrary, displacements of a higher order of magnitude, for example 1 cm, are possible without reaching the maximum static shear strength of the interface, since if the test is interrupted, the block remains substantially in the position reached thus far. Therefore, considering the experimental behaviour, the parameter ϕ_0 is not very significant, in this case, in contrast to ϕ_{stand} that has a relevant role. In some extreme cases, when the interface failure is not reached even with a 50 mm displacement, ϕ_{stand} could be seen as a kind of deformation limit state.

It should be emphasised that it is very important to distinguish between gradual and uneven sliding behaviours, given that, as shown, the significant friction parameter is completely different. In case of any doubts about the actual kinematics, it may be useful to associate the standard inclined plane test with a further test, in which the rise up of the plane is interrupted in correspondence with a block displacement of 1 mm and the following block displacements are monitored for a period of 1 h at least.

In conclusion, being able to define a univocal criterion of interpretation of the inclined table test, at this stage, does not seem possible since the test interpretation should consider the proper kinematics of the interface, which, in turn, depends on the nature of the polymers, which are in contact with each other. On the other hand, the inclined plane test was successful in revealing the real interface behaviour that is not possible in the direct shear test in which the movement occurs at a constant sliding speed. In fact, regardless of the different stress range, given that direct shear tests are usually performed at medium-high normal stresses (>25 kPa), the main difference is related to the way in which the shear stress is applied to the interface. In the case of the direct shear test a pre-set sliding speed is imposed and the interface response is measured in terms of the shear stress developed by the contact. On the contrary, in the case of the inclined plane test, a gradually increasing shear stress is applied to the interface, as the inclination of the plane increases, and the response is measured in terms of displacement. This apparently minor difference implies that the various sliding mechanism responses of the interfaces can be highlighted only with the inclined plane test, which, in spite of all the limits of this type of device, presents the great advantage of allowing to test with kinematic conditions that are similar to those of the real failure. To obtain with a direct shear test similar results to those obtained with the inclined plane would imply to carry out tests at various pre-set speeds, provided that the range of the real speeds could be replicated with the direct shear device. It should be underlined that the average sliding speed observed in our experimental conditions, in the range of displacement between 15 mm and 50 mm, was equals to 0.9 mm/min (Fig. 17). This speed is comparable to that established for the direct shear test (1 mm/min) and consequently the friction measured with the direct shear device could not correctly identify the static strength of this type of interface.

As a final note, the results highlighted a certain degree of uncertainty in the evaluation of the interface shear strength upon repeating the tests. The data scattering observed was more or less conspicuous for the various interfaces and may depend on the inherent variability of the material, even among specimens from the same manufacturing lot. In addition, a certain degree of uncertainty may arise from measurement

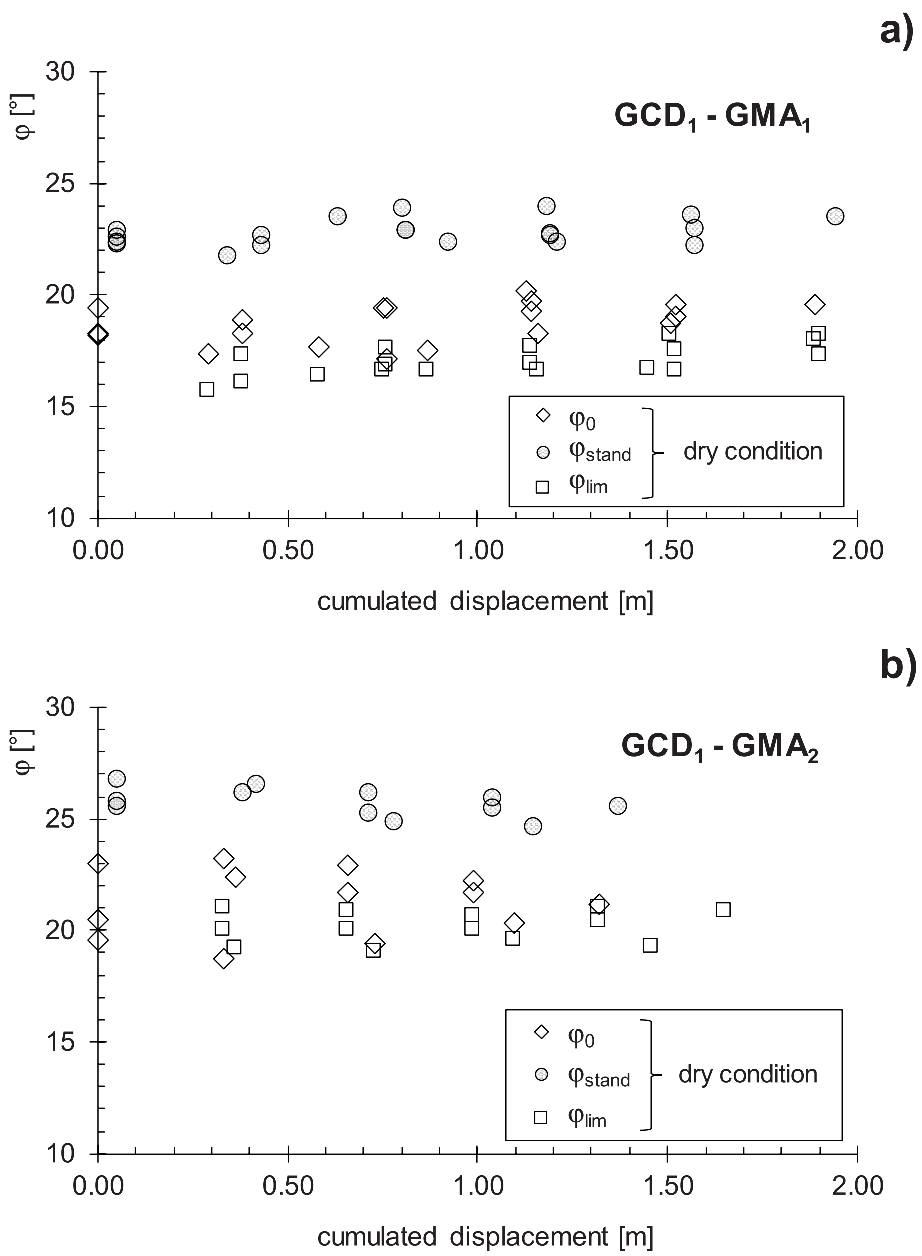

Fig. 14. Shear strength angles as a function of cumulated displacement for the two types of GMA interfaces exposed to dry conditions and following repeated tests.

errors, which are the sum of bias in average property measurements and random errors, from minimal differences in the test procedure, or from certain environmental factors not taken into consideration. This variability should be taken into account in the design, even if there can be different approaches to the problem (Dixon et al., 2002). A common design practice is based on the selection, by the engineer, of a conservative value of the mean interface shear strength or, in other words, by using engineering judgement. Conversely, another approach is that of using the characteristic strengths obtained via statistical analysis of the measured values (Sia and Dixon 2007), as proposed for example by the Eurocode 7 (1997), although it requires a sufficient number of tests to enable statistical analysis. In this regard, an interesting discussion on the interface shear strength variability and its use in reliability-based analysis is provided by Dixon et al. (2006). They suggested an alternative approach that arranges interface shear strength values obtained from a limited number of specific tests with the literature information available on the variability of the shear strength parameters for each type of interface.

5.2. *Some considerations about the force procedure*

The force procedure generally provides the minimum values of shear strength, which are even lower than those of ϕ_0, so that it could be adopted as an interesting alternative criterion for interfaces exhibiting a gradual sliding behaviour. Limited to the case of the GMB_S-GCD_1 interface, several tests have been conducted with the modality as previously described, that is, by interrupting the increase of the plane elevation at a given inclination and by monitoring the displacement of the block for a time interval of at least 30 min. Although the results should be interpreted with caution, mainly due to the dispersion of the experimental data set, the shear strength angles provided by the force procedure appears to correspond to an inclination for which a transition takes place between a static condition and one characterised by very slow movements. Obviously, further experimental feedback is needed, also concerning other interfaces exhibiting a gradual sliding behaviour, in order to confirm these preliminary results.

Moreover, another relevant aspect should be highlighted regarding

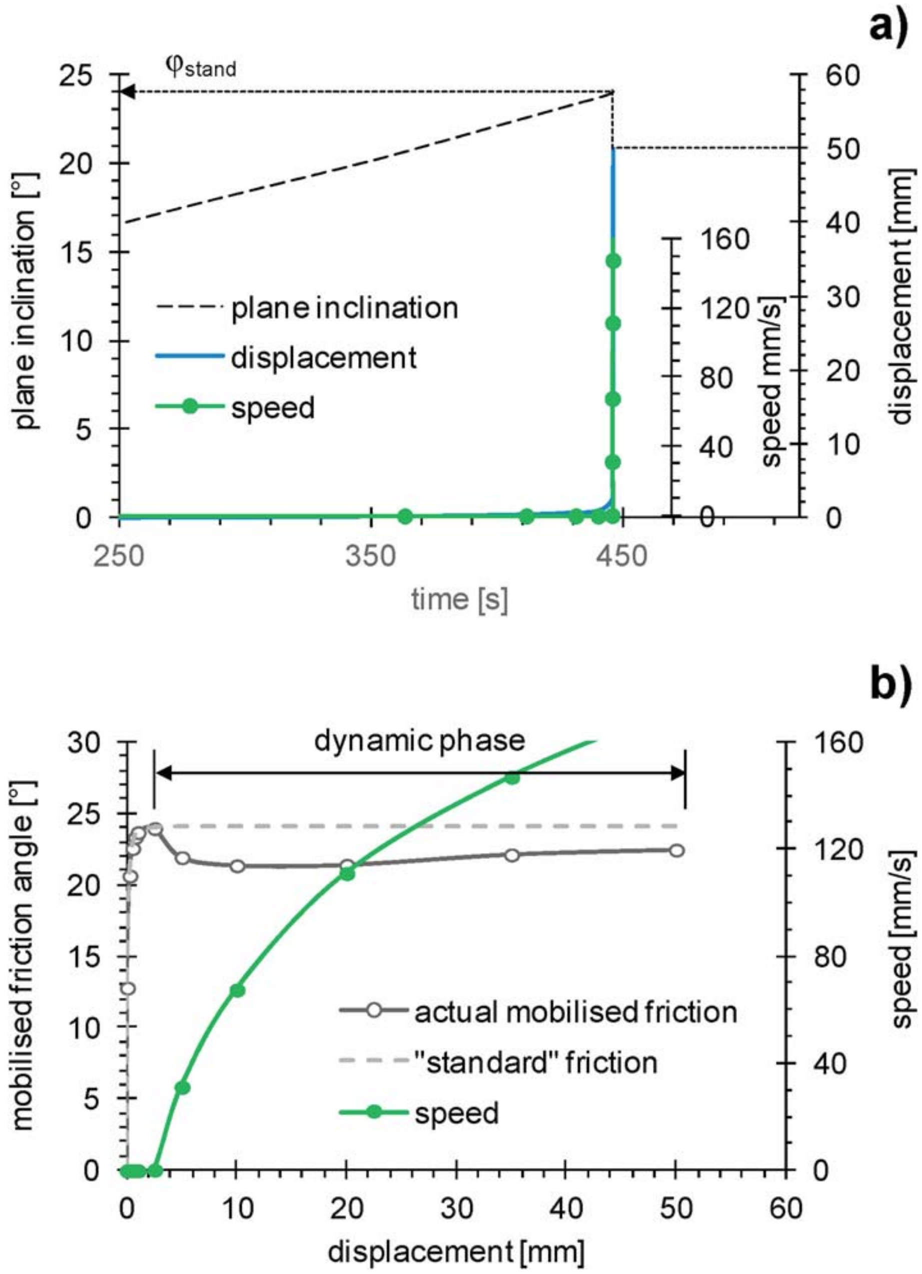

Fig. 15. Typical inclined plane test for an interface characterised by a sudden sliding motion (e.g. the GMB_T-GCD_1 interface: (a) plane inclination, block displacement and speed vs time; (b) mobilised friction and block speed vs displacement.

the force procedure. In the work of Briançon et al. (2011), tests were performed at various rising speeds of the plane, which did not show a dependence of the result on the rotation speed. However, some observations, conducted during this experimental research, led the authors to believe that also the physical phenomena, connected to the force procedure, may be affected by a time factor.

In this respect, when the GMB_S-GCD_1 interface was tested in dry conditions keeping the plane at a fixed inclination (18.1°), instead of continuously varying the plane inclination as proposed by Briançon et al. (2011), the force exerted by the constraint cable was observed not to be constant but to vary with time (Fig. 18). In this case, the time scale started from the moment this inclination was reached and the monitoring period was extended to about 50 h. As the figure shows, the mobilised friction and the retaining force are inversely related to each other; in fact, a slow increase of the force with time corresponds to a progressive reduction of the mobilised friction. This result demonstrates that the friction mobilised by the interface is not constant so that the result of the force procedure may be considered a sort of balance in which the tendency of the friction to change over time is concealed by the continuous variation of the shear stress, due to the increase in the plane inclination. For this reason, further studies should be promoted to highlight the physical meaning of the parameter ϕ_{lim}.

5.3. Influence of the wear effect (mechanical damage)

Geosynthetic interfaces can be sensitive to the wear process, which can induce an alteration of the surface finish and, consequently, of the friction angle, which may thus increase or decrease (De and Zimmie, 1998; Kim et al., 2005; Pitanga et al., 2013; Stoltz and Vidal, 2013). Relative displacements between two geosynthetic layers can occur, for example, during the installation phase or may be induced by the different tensile stiffness in relation to the stress mobilisation. In this

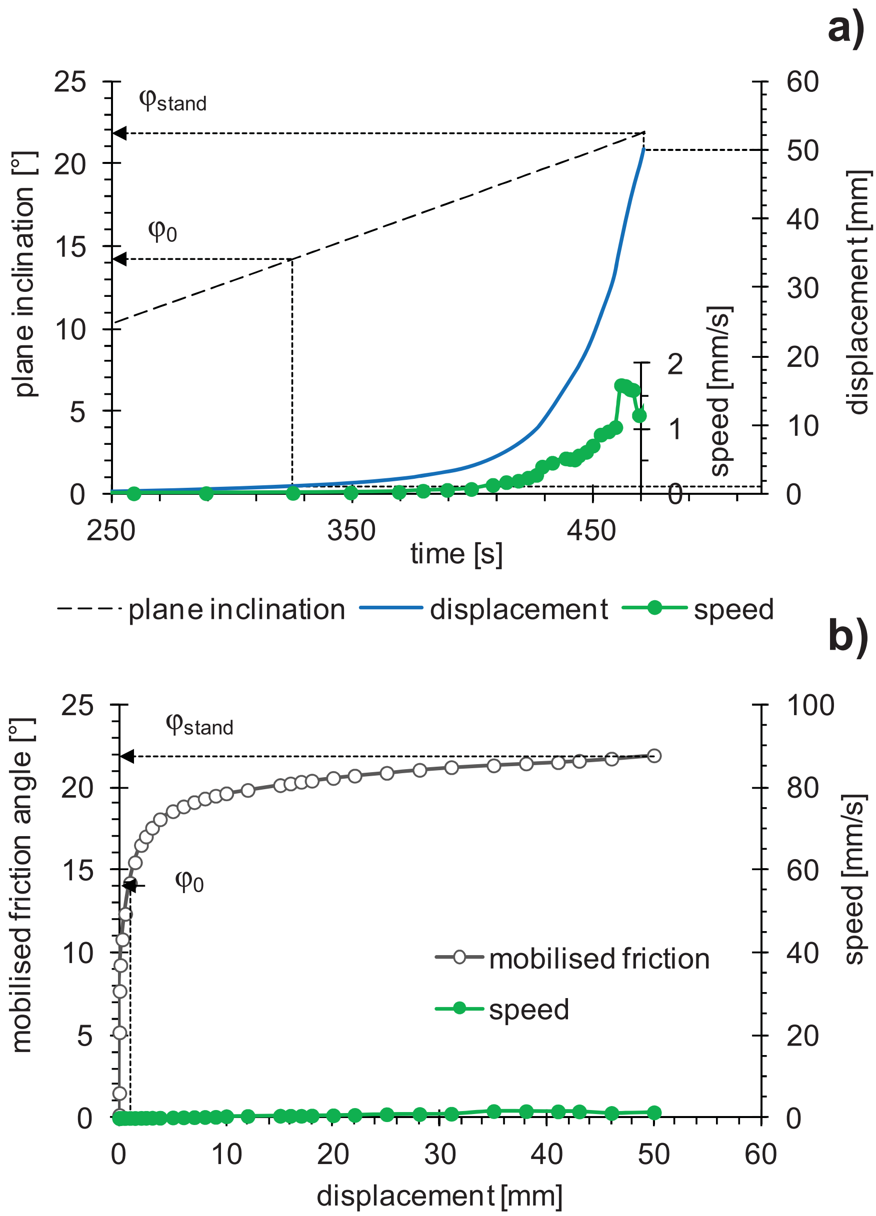

Fig. 16. Typical inclined plane test for an interface characterised by a gradual sliding behaviour (e.g. GCD_1-GMA_1): (a) plane inclination, block displacement and speed vs time; (b) mobilised friction and block speed vs displacement.

study, as already described, the wear effect was analysed by performing repeated inclined plane tests, i.e. by conducting additional shear passes on a same pair of specimens. The change in interface friction can be assessed by using a wear index (WI), which is defined as the percentage difference in the tangents of the interface friction angles from the retested conditions to the virgin conditions (Eq. (3)).

$$WI = \frac{\tan \phi_{retested} - \tan \phi_{virgin}}{\tan \phi_{virgin}} \quad (3)$$

Negative values of the WI are indicative of a loss of interface friction following the cumulated displacement, whereas positive values indicate an interface friction gain.

Table 3 offers a summary of the wear effects for the studied interfaces, comparing the average values of the different friction angles, assessed on virgin specimens and after a displacement of at least 1.0 m. Since the length of the travel block was not the same in all the tests carried out, the first available data set, which was characterised by a cumulative displacement equals to or greater than 1.0 m, was taken as a reference. As summarised in Table 3, the wear effect solicited different responses according to the interface taken into consideration: some interfaces, such as the GMB_T-GCD_1, showed a marked reduction in friction, others, such as the GMB_S-GCD_1, were apparently unaffected, and others still (e.g. the GCD_2-GCL_{nw} interface) exhibited a significant increase in friction following the cumulated displacement. The maximum percentage reduction in the friction coefficient was equals to 17.7% (GMB_T - GCD_1 interface, ϕ_0 parameter), while the maximum percentage increase observed reached a value of 17.1% (GCD_2 - GCL_{nw} interface, ϕ_0 parameter).

The wearing effects, highlighted by the repeated tests, are another way to show the interface shear strength reduction highlighted in the past by direct shear tests carried out at large deformations. More in general, to understand the mechanisms that govern the phenomena of

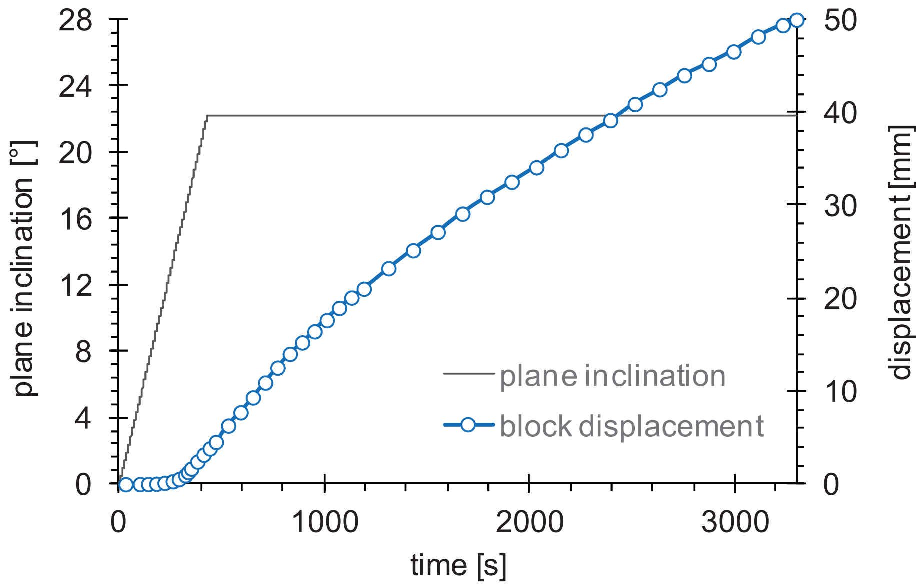

Fig. 17. The plane inclination and block displacement in relation to time in a variant of the inclined plane test for an interface (GCD_1-GMA_1) showing a gradual sliding behaviour.

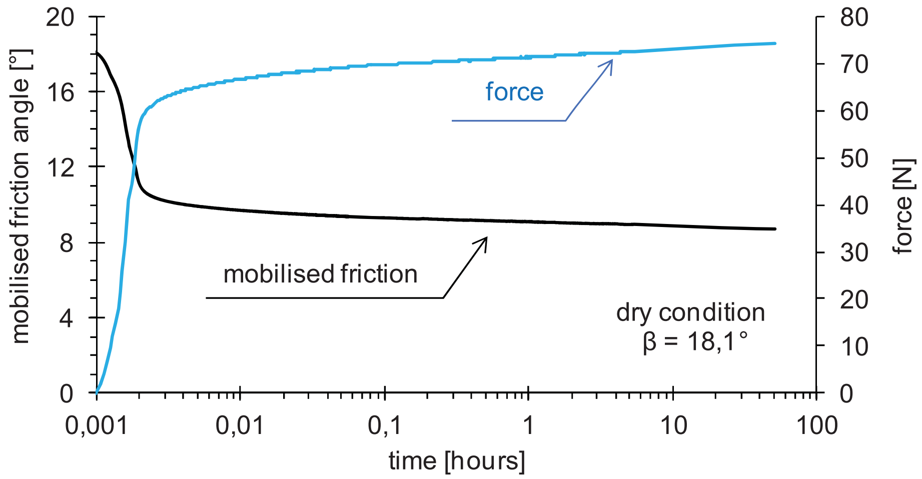

Fig. 18. The retaining force and mobilised friction angle as a function of time in a variant of the force procedure at a constant plane inclination.

Table 3
Effect of wear on the interface friction angles for repeated inclined plane tests.

interface	interface condition and status		previous block displ.	$\phi_{0\ average}$	WI (tan ϕ_0)	$\phi_{stand\ average}$	WI (tan ϕ_{stand})	$\phi_{lim\ average}$	WI (tan ϕ_{lim})
			(m)	(°)	(%)	(°)	(%)	(°)	(%)
GMB_S - GCD_1	dry	virgin	0	13.2	3.9	15.2	−0.7	12.3	1.7
		retested	1.0	13.7		15.1		12.5	
	wet	virgin	0	10.9	−1.9	11.5	−5.3	9.8	−6.2
		retested	1.0	10.7		10.9		9.2	
GMB_T - GCD_1	dry	virgin	0	24.2	−17.7	24.8	−14.3	16.4	−5.1
		retested	1.0	20.3		21.6		15.6	
GMB_R - GCD_1	dry	virgin	0	25	−5.4	36.9	−12.2	25	4.1
		retested	1.0	23.8		33.4		25.9	
GCD_2 - GCL_w	dry	virgin	0	28	−2.9	30	6.1	23.9	−1.4
		retested	1.0	27.3		31.5		23.6	
	wet	virgin	0	22.2	−4.0	23.3	−9.0	17.7	0.6
		retested	1.0	21.4		21.4		17.8	
GCD_2 - GCL_{nw}	dry	virgin	0	26.7	17.1	30.9	8.9	25.6	−0.9
		retested	1.0	30.5		33.1		25.4	
GCD_1 - GMA_1	dry	virgin	0	18.7	5.8	22.6	3.0	16.4	3.2
		retested	1.0	19.7		23.2		16.9	
GCD_1 - GMA_2	dry	virgin	0	21	1.0	26.1	−3.5	20.1	0.5
		retested	1.0	21.2		25.3		20.2	

surface wearing, the investigation can be pushed to a microscopic scale. In this regard, various studies have been carried out in the past, aimed at characterising the roughness of geosynthetics (Dove and Frost, 1996; Dove et al., 1996) and at studying the surface changes due to the mutual rubbing. Referring to the latter, research has been conducted in depth concerning, for example, the interaction between various types of geomembranes and nonwoven geotextiles (Frost and Lee, 2001; Kim and Frost, 2007). These studies have revealed that for the textured geomembranes, the residual condition develops in relationship to the wearing of the micro-texture asperities, gradually guillotined by the geotextile filaments. The true residual condition can be achieved only after all these weak micro-texture features are removed, and only relatively stronger macro-textures are able to hold the geotextile filaments. Moreover, by using advanced image analysis techniques, it was possible to observe the inner structure of the interface, highlighting significant variations of geotextile filament structure owing to the localised stretching and surface degradation around texture elements. Finally, the works of Li and Gilbert (2006) and Manheim et al. (2015) have confirmed that post-peak strength reduction for textured geomembrane-nonwoven geotextile interfaces is primarily due to a small-scale wearing of the geomembrane texture.

Conversely, an opposite behaviour, consisting of an increase of shear strength with wear level, was found in this work for the interface GCD_2-GCL_{nw} in dry conditions (Fig. 9b); it should be noted that, in this case, the contact was actually between the nonwoven geotextile of the GCD_2 and the nonwoven geotextile of the GCL_{nw}. The visual observation of the surfaces following the shear displacement revealed a progressive separation of fibres from both geosynthetics, which can explain the increase in friction.

Some useful suggestions on suitability by using peak or worn (residual) shear strengths for the design of geosynthetic-lined slopes, can be found in Stark and Choi (2004).

6. Conclusions

The laboratory investigation, here presented, which was performed on seven different geosynthetic interfaces in conditions of low normal stress, highlights how the response to the shear stress acting on the interfaces can be very different, depending on the materials and the finishing of the surfaces that are in contact.

During the inclined plane tests, three main sliding mechanisms were identified, which were indicated as *sudden sliding*, *gradual sliding* and *uneven sliding*, corresponding to three different modes of friction development in relation to the imposed shear stress. If, on the one hand, the evidence of various sliding behaviours implies that a unique interpretative criterion for the inclined plane test is hardly possible, on the other hand, the same observation reveals that this device is indeed suitable and effective in providing supplementary information on the interface's behaviour compared to other types of tests. In fact, despite the intrinsic limits of this type of device, the inclined plane test is successful in reproducing loading conditions during the test, which are similar to those found in situ, thus pointing out the kinematics of failure.

In the case of interfaces with a *sudden sliding* behaviour, the ϕ_{stand} parameter, although neglecting the dynamic effects, is considered useful and reliable in the evaluation of the friction since it substantially provides the value of the peak friction angle.

In the case of *gradual sliding* interfaces, the ϕ_{stand} parameter, in contrast, dangerously overestimates the shear strength available, given that it is associated with a motion rather than a static condition. For these interfaces, instead, referring to the ϕ_0 parameter, obtained at a displacement of 1 mm, would be more advisable provided that it is adopted in combination with an adequate safety factor to avoid very slow movements.

For the *uneven sliding* interfaces, the reference parameter should again be the ϕ_{stand} angle.

As regards the force procedure, it generally provides the most conservative friction assessment and, for this reason, the value of ϕ_{lim} may be a valid alternative to the parameter ϕ_0 in the case of interfaces with a gradual sliding behaviour. Moreover, the experiments performed on this procedure showed a variation in time of the mobilised friction due to long-term viscous phenomena. In any case, further studies should be promoted on the physical meaning of the force procedure.

Finally, the results of the tests revealed the repeatability of the different friction parameters and their variability in relation to the mutual rubbing of the surfaces. The latter effect generally induced a reduction in the friction available, even if an opposite behaviour was observed in some interfaces with an increase in interface friction that was proportional to the increase in shear displacement. In any case, considering the inevitable rubbing related, for example, to the in situ installation phase, the possible reduction of friction suggests the opportunity to test the specimens not only in virgin but also in worn conditions.

The repetition of the tests, for two interfaces, in wet conditions, showed that the state of hydration brought to a significant reduction in the friction available. Also in this case, experimenters should pay more attention to selecting the laboratory test conditions that best suit and reproduce the real conditions of use of the materials.

Concluding, the study shows the potential of the inclined plane device, which, despite some intrinsic limitations, constitutes a valid tool to understand the behaviour of the interfaces between geosynthetics. In this perspective, further studies are desirable to clarify the aspects that still remain critical with the aim of obtaining a reliable laboratory prediction of the interface friction, which is available in conditions of low normal stress.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Notations

β	inclination of the plane
β_0	inclination of the plane when the block performs a displacement of 1 mm
β_{50}	inclination of the plane when the block performs a displacement of 50 mm
ϕ_0	angle of friction at "first movement"
ϕ_{stand}	"standard" friction angle according to EN-ISO 12957–2 (2005)
ϕ_{lim}	limit friction angle according to the force procedure
ϕ_{dyn}	dynamic friction angle
ϕ_{virgin}	friction angle evaluated on virgin specimens
$\phi_{retested}$	friction angle evaluated on retested specimens
a	block acceleration along the plane
g	gravity acceleration
F	tensile force in the cable
W	weight of the block
σ_{v0}	initial vertical stress
σ_{va}	average normal stress applied at the interface
WI	wear index

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