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EVALUATION OF GEOSYNTHETIC INTERFACE FRICTION AT LOW NORMAL STRESS: COMPARISON BETWEEN TWO DIFFERENT TEST PROCEDURES

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ABSTRACT

The interface friction between geosynthetics has previously been extensively studied with reference to medium-high contact stresses. The interface strength at low contact stress is a less investigated chapter whose importance, however, is evident for the stability of geosynthetic landfill barriers during the construction stage and of the covering systems. The inclined plane is the most used laboratory test for measuring the geosynthetic interface friction at normal stresses as low as 5 kPa. This type of test, however, is not free from criticalities, due to the non-uniformity of the contact stresses induced by the inclination of the plane. Alternatively, it is possible to extrapolate the results of the classic direct shear test, which, however, generally cannot be performed at such low contact stress values. The paper compares data results provided by inclined plane tests and an experimental apparatus capable of performing horizontal shear tests at a vertical stress of 5 kPa. The peculiarity of this device is to guarantee a constant growth rate of the tangential stress equivalent to what happens with the inclined plane test. The good agreement of the interface strength data obtained for two different geosynthetic interfaces leads the way for possible future innovations and insights on the topic.

Key words: geosynthetic, interface fiction, inclined plane, direct shear

INTRODUCTION

The interfaces between geosynthetics represent a potential sliding surface for the works that include them, given the low friction values that these materials can generally mobilise. This is an important aspect that must be considered in the design stage and which can cause serious damage if not properly addressed. However, a few types of tests are suitable for measuring the interface friction at very low normal stress: one of these is the inclined plane test, usually performed under a vertical stress of 5 kPa. Since this type of test is not without its criticalities, the work compares the results obtained from inclined plane tests and those provided by a different experimental apparatus capable of performing horizontal shear tests at very low normal stress.

MATERIAL AND METHODS

Direct shear device versus inclined plane apparatus

According to the standards ASTM D5321-8 (ASTM International [ASTM], 2021) and EN ISO 12957-1 (International Organization for Standardization [ISO], 2005a), the direct shear test is usually performed on

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specimens of 300 × 300 mm in size, fixed horizontally to two parts of the device, one of which is stationary during the test while the other slides on it.

The test is developed under a preset value of the normal stress, through a standardised movement of the sliding part, at a constant speed of 1 ±0.2 mm·min^{-1}, while the contrasting force, necessary to keep the other half of the device is measured until a maximum displacement of 50 mm is achieved. The test must be carried out under at least three different values of normal stress (i.e. for the European standard 50 kPa, 100 kPa and 150 kPa), thus allowing to delineate the failure envelope and the evaluation, by linear interpolation of the data, of the parameters of friction (c', φ).

Another type of test for the interface friction evaluation is the inclined plane test (Lalarakotoson, Villard & Gourc, 1999; Reyes Ramirez & Gourc, 2003; Pitanga, Gourc & Vilar, 2009; Carbone, Gourc, Carrubba, Pavanello & Moraci, 2015), standardised by the European standard EN ISO 12957-2 (ISO, 2021b). As indicated by the name itself, a plane, which can be tilted at will, and a steel box, free to slide over the plane, constitute the main elements of the device used for this type of test. The sliding motion of the upper box can be led by lateral guides or vertical carriages, acting outside the area of contact between the two geosynthetics. One specimen is bound on the inclined plane while the other is fixed to the bottom of the box and, according to the EN ISO 12957-2 (ISO, 2021b) and in analogy with the direct shear test, the specimens have a minimum size of 300 × 300 mm. Starting from an initial configuration with the plane horizontal, the inclination is gradually increased, at a constant speed of 3 ±0.5°·min^{-1}. During the increase of the slope of the plane, the time and the inclination angle at which the upper box slides are evaluated. In detail, following the recommendations of the EN ISO 12957-2 (ISO, 2021b) the inclination angle β reached by the plane in correspondence with a displacement of the upper box of 50 mm must be taken equal to the friction angle of the interface:

$$\tan \varphi = \tan \beta_{50\text{mm}}. \quad (1)$$

It should be noted that the displacement of 50 mm constitutes an arbitrary reference, probably selected in analogy with the maximum displacement of the direct shear test. Moreover, Eq. (1) is based on the hypothesis of a static equilibrium while the condition, at this stage, is more properly kinematic, given that the upper box is sliding along the plane, with speed and acceleration that in some cases are not negligible (Gourc & Reyes-Ramirez, 2004).

These two types of tests, the direct shear and the inclined plane, differ from each other in various aspects. First of all, for the normal stress range investgated: for the direct shear, it generally may vary between extreme values of approximately 25 kPa and 500 kPa, while it is very difficult to control very low normal stress values, due to the way of applying the normal force utilising a hydraulic press. Conversely, the inclined plane test is performed only at very low normal stress, generally equal to 5 kPa. Referring to the equivalence between the two types of tests, the direct shear and the inclined plane, the different normal stress ranges studied make difficult a direct comparison of the results. However, observing the data reported in some papers (Wasti & Özdüzgün, 2001; Ferreira, Vieira & Lopes, 2016), it seems that the extrapolation of the results of the direct shear tests to the range of very low normal stresses may overestimate the shear resistance of the interface with respect to the friction parameters provided by the plane inclined tests. It should not be forgotten that the failure envelope of the geosynthetics interfaces can be curvilinear, and therefore, the choice of the type of laboratory tests should be correlated to the real level of stress to which the interface will be subjected on site. For example, using the results of a direct shear test, performed as mentioned at medium-high stresses, for the design of the cover of a landfill, characterised by very low normal stresses, may be unsafe. Similarly, it could be the opposite case of extending the data obtained from inclined plane tests to a condition of high normal stresses, such as that of lateral liners. Another aspect related to the investigated normal stress is that the direct shear test is carried out at three different values of normal stress, thus allowing to delineate the failure envelope and to evaluate the tangent friction angle. On the contrary, the inclined plane test investigates a unique value of normal stress, the reason why it can give only the value of the secant friction angle.

In addition to the different stress ranges, the difference between the results provided by the two test methods may be ascribed to the different ways of applying the shear stress. In fact, in the direct shear, the displacement increases at a constant imposed speed of 1 mm·min^{-1} while the interface's response is detected in terms of opposing force, equal to the friction mobilised at the contact surface.

Conversely, in the inclined plane test, the shear stress gradually increases, depending on the imposed slope of the plane, while the displacements of the interface are measured. In summary, in the first case, a displacement is imposed, and a force is detected, while in the second case, a stress is imposed, and a displacement is detected. Few studies are currently available on this topic (Stoltz, Nicaise, Veylon & Poulain, 2019), i.e. on the effects of how the stress is applied during an interface test. However, it is intuitive that the approach followed in the inclined plane test is much more similar to the real kinematics involved in the sliding of an interface on a slope.

To complete the discussion of the pros and cons of the two types of tests, it is necessary to remember that the achievable hydration conditions of the interface are different in the two tests. For the direct shear device, the test can be performed on both dry and immersed conditions, while in the inclined plane device, dry and humid conditions can be replicated, but not the totally immersed one, unless placing the apparatus in a cistern, a solution in fact not practicable, or unless introducing a seepage motion at the interface (Briançon, Girard & Poulain, 2002).

Another aspect to take into account is the maximum displacement allowed by the various devices. For the direct shear, the standard provides for a minimum displacement of 50 mm, and this recommendation influences the maximum stroke of the devices, which, in general, is slightly higher than the value indicated by the standard. However, this level of displacement may not be large enough to mobilise the residual shear strength (Stark, Williamson & Eid, 1996). The level of displacement experienced by the interface can be increased only by performing many cycles of displacement with motion reversal. On the other hand, this method does not correspond to the real physics of the mutual sliding of the materials since it involves a different action on the microscopic asperities and on the fibres of geosynthetics at each inversion of the direction of the motion. For these reasons, there are some experimental direct shear devices which allow investigation of greater displacements (Baykal, 2016). The tests on an inclined plane do not have this limitation since the maximum displacement experienced by the interface can be several tens of centimetres, depending only on the length of the plane on which the box slides and which can be further increased by repeating the slips several times, after having returned the box to its initial position. To be fair, even the inclined plane has some negative aspects: one of them is a potential issue related to the eccentricity of the normal force. In fact, as the inclination of the plane increases, the raised position of the box's centre of gravity causes an increasing eccentricity of the normal force acting on the interface. Although for the usual geometries, this effect should not lead to an excessive variation of the normal stresses (Palmeira, Lima & Mello, 2002), the EN ISO 12957-2 standard (ISO, 2021b) advises the use of some preventive measures, such as wedges or inclined sides, in order to reduce the eccentricity of the normal force as much as possible.

As seen, the two types of tests each have advantages and disadvantages, and for this reason, a different device is presented in this paper, designed to study the interface friction between geosynthetics at low normal stresses, overcoming some inherent defects and limitations of the inclined plane test. This equipment allows performing tests in conditions of increasing tangential force, as happens in the inclined plane, avoiding, however, the problem of the eccentricity of the normal load and allowing the study in immersed conditions. In order to validate this test method, the results obtained for two different interfaces will be presented and compared with those provided by the usual inclined plane tests.

Direct shear device versus inclined plane apparatus

This study is based on two different pieces of equipment available at the geotechnical laboratory of the ICEA Department, University of Padua. The first is an apparatus of a new design, similar to a direct shear but with a different approach for the method of application of the shear stress (Fig. 1). It consists of a steel box with sides of 0.30 × 0.30 m placed on a horizontal plane. The first geosynthetic specimen is fixed to the base of the box, while the second is fixed on a plane.

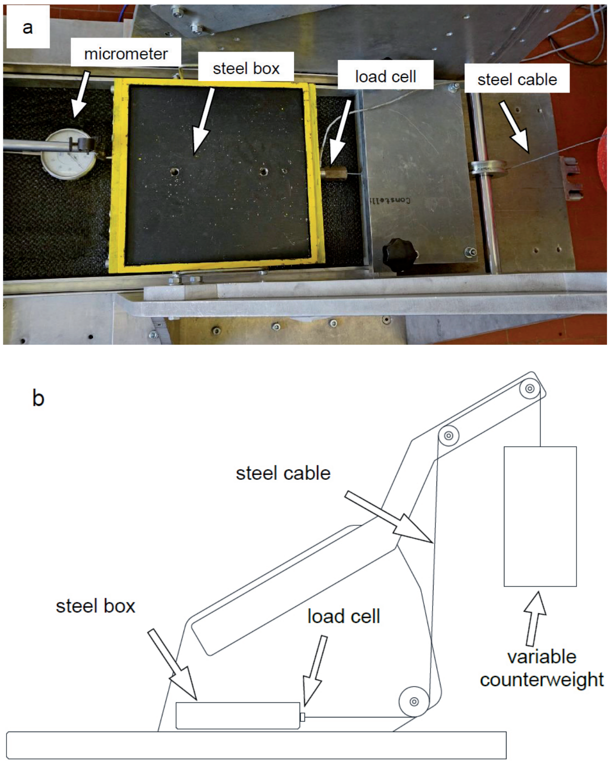

Fig. 1. The direct shear SSI apparatus: a – view from the top; b – sketch

Source: own work.

The box is connected using a steel cable, to a counterweight. A load cell, interposed between the box and the cable, allows measuring the horizontal force acting on the box moment by moment. During the test, the weight of the counterweight gradually varies over time and ends when the box reaches a displacement of 50 mm, which is monitored by means of a centesimal micrometre. Under the hypothesis of a static condition, the mobilised friction angle can be evaluated, time by time, by using the following simple equation:

$$\tan \varphi = \frac{H}{W}, \qquad (2)$$

where:
H – measured horizontal force applied to the box,
W – weight of the box.

In order to highlight that this is not about a usual direct shear test, the test following this test will be referred to as a direct shear SSI test, where the acronym SSI indicates that the experiment is performed following shear stress increase.

The second device is a well-known inclined plane device (Fig. 2), with a plane length of 1.10 m and a width of 0.25 m. Lateral guides ensure the straight sliding of the box without introducing significant additional friction forces. Instead of the standard box of 0.30 × 0.30 m, a different shape (0.21 × 0.42 m) was adopted, having the same contact area of approx. 0.09 m^2 but with a rectangular contact area in order to minimise the possible effects of the normal load eccentricity. With the same purpose, the height of the centre of gravity of the box, able to apply a normal load of 5 kPa, is only 3.4 cm.

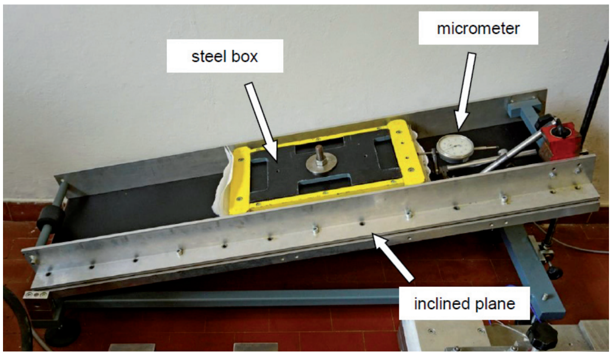

Fig. 2. The inclined plane device

Source: own work.

Direct shear device versus inclined plane apparatus

In this research, two interfaces between geosynthetics were studied. A first interface is formed by the contact between a smooth HDPE geomembrane (GMBs) and a drainage geocomposite (GCD). The geomembrane has a thickness of 1.5 mm, a mass per unit area of 1,420 $g \cdot m^{-2}$ and tensile strength of 47 $N \cdot m^{-1}$. The drainage geocomposite is formed by a draining body enclosed between two nonwoven geotextiles made of polypropylene; it has a thickness of 5.5 mm under a pressure of 2 kPa, a mass per unit area of 900 $g \cdot m^{-2}$ and tensile strength (equal to MD and CMD) of 20 $kN \cdot m^{-1}$.

The contact between two specimens of the same woven geotextile, made of polypropylene, having a mass per unit area of 400 $g \cdot m^{-2}$ and tensile strength (MD) of 90 $kN \cdot m^{-2}$, is the second interface studied.

All tests were carried out in dry conditions, at a laboratory temperature of 20 ±2°C and under normal stress of 5 kPa.

RESULTS AND DISCUSSION

Referring to the first interface, between the smooth HDPE geomembrane and the drainage geocomposite (GMBs-GCD), Figure 3 shows, as an example, the results of an inclined plane test carried out on virgin specimens, in terms of displacement of the box in the function of the plane inclination. According to Eq. (1), the angle of plane inclination is always equal to the mobilised friction angle, because the data interpretation is performed by assuming a static condition when the box slides along the plane.

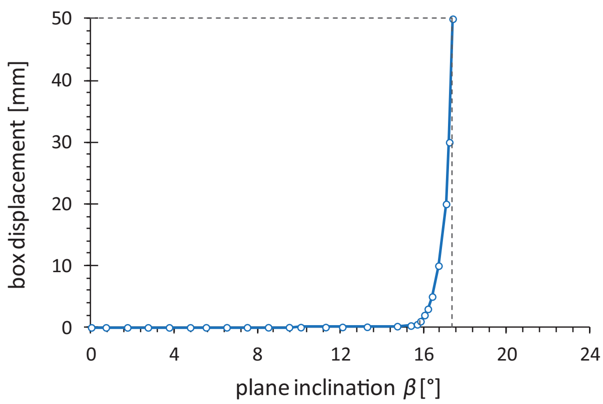

Fig. 3. Typical results of an inclined plane test on the GMBs-GCD interface

Source: own work.

An example of a direct shear SSI test on the same interface and again on virgin specimens is reported in Figure 4. In detail, Figure 4a shows the evolution of the applied horizontal force and the corresponding box displacement in the function of the time, while Figure 4b shows the mobilised friction angle and the box speed in the function of the box displacement. Also, in this case, the evaluation of the interface friction was made assuming a static equilibrium of the box (Eq. 2), operating with the same criterion normally adopted in the case of the inclined plane test, even when its speed is not actually negligible.

To investigate the wear effect of the surfaces due to mutual sliding (Pitanga, Vilar & Gourc, 2013; Pavanello & Carrubba, 2016), the tests were repeated many times on the same specimens. The first evaluation relates to a virgin condition; the subsequent ones were performed by sliding the block again from the initial position, thus correlating friction parameters to the amount of cumulative displacement experienced by the interface. The comparison of the results for the two conditions and the two types of tests is shown in Figure 5 in terms of the friction angle evaluated, during each test, for a box displacement of 50 mm. The data show a good correspondence between the two types of tests, with slightly lower values provided by the direct shear test. Moreover, this interface shows a moderate reduction of the available friction as the cumulated displacement increases, and this trend is similar for both test methodologies.

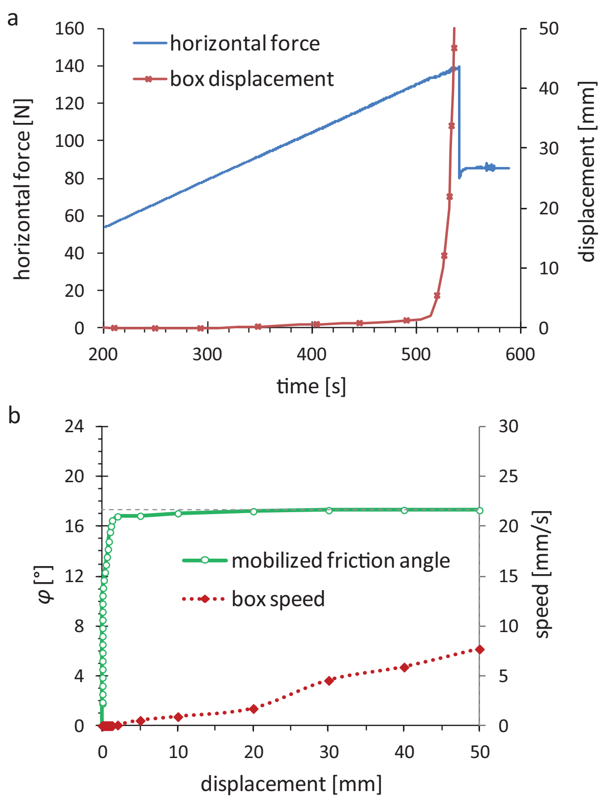

Fig. 4. Results of a direct shear SSI test on the GMBs--GCD interface: a – horizontal force and box displacement over time; b – mobilised friction angle and box speed in function of displacement

Source: own work.

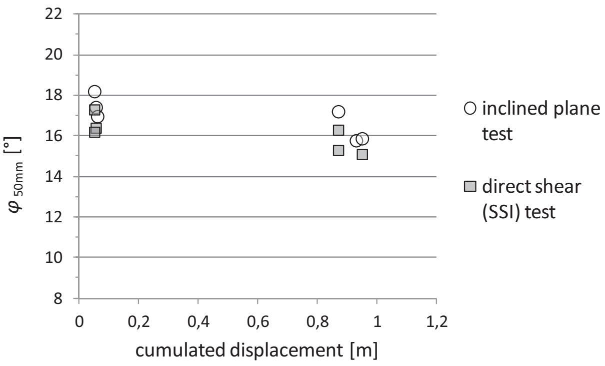

Fig. 5. Summary of results for the GMBs-GCD interface vs cumulated displacement

Source: own work.

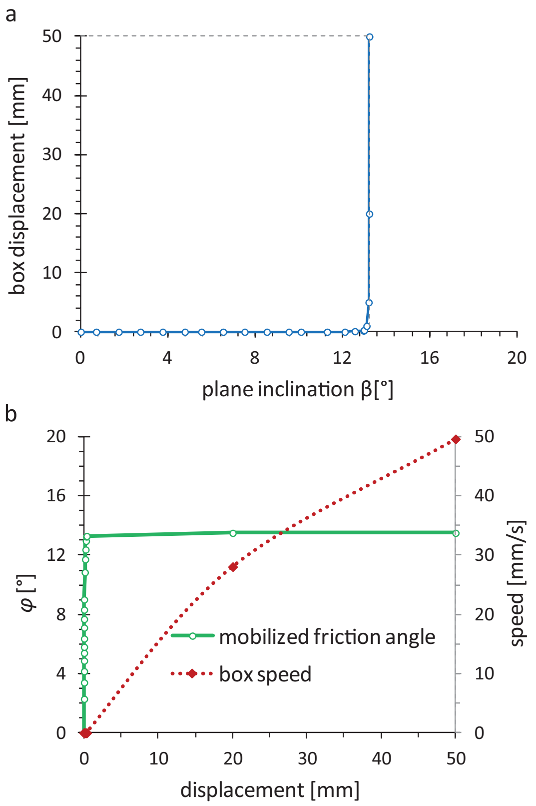

Fig. 6. Typical results for the GTXw-GTXw interface: a – inclined plane test; b – direct shear SSI test

Source: own work.

An example of the results obtained for the second interface between two specimens of woven geotextile (GTXw-GTXw) is shown in Figure 6. Figure 6a shows the results of an inclined plane test, on virgin specimens, in terms of displacement of the box in the function of the plane inclination, while Figure 6b shows the results of a direct shear SSI test, again on virgin specimens, in terms of mobilised friction angle and box speed, in the function of the displacement. Even in this case, a similar interface behaviour can be observed in the two types of tests.

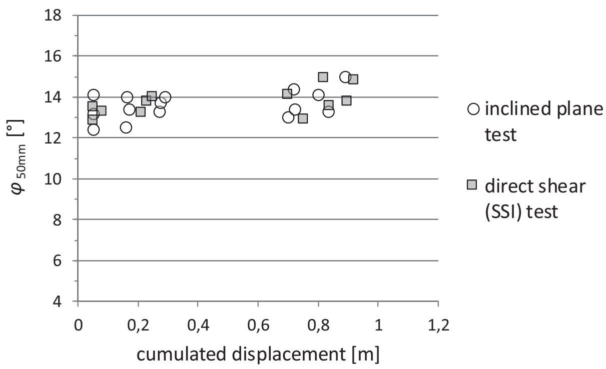

Fig. 7. Summary of results for the GTXw-GTXw interface

Source: own work.

Lastly, Figure 7 shows a graphical comparison of the results provided by the two types of tests as a function of the cumulated displacement or, in other terms, of the experienced wear. As can be seen, the two results of the two test procedures show a very good agreement in terms of both average value and data scattering. Finally, unlike the previous one, this interface exhibits a slight increase in the available friction as the cumulated displacement increases.

CONCLUSIONS

The geosynthetic interface strength at low contact stress was investigated in this paper by performing the tests with the inclined plane and with an experimental direct shear device. Two interfaces were tested, one made by a smooth HDPE geomembrane coupled with a drainage geocomposite (GMBs-GCD), and another made by coupling two woven geotextiles (GTXw-GTXw). The following conclusions can be drawn thanks to the good correspondence of results with the two testing methods. The eccentricity of the normal load, related to the table tilting during the inclined plane test, does not involve significant changes in the results compared with the direct shear SSI test, in which the normal load is centred because the sliding plane is always horizontal. This is true if the box of the inclined plane test is well designed, with a low centre of gravity, and the test does not require achieving excessive inclination angles of the table.

The direct shear SSI test, carried out with the experimental device at constant loading speed, is a valid alternative to the inclined plane test for measuring the geosynthetics interface friction at low normal stress. It should be emphasised that the current direct shear test devices generally operate at normal stresses higher than 25 kPa and under imposed displacement speed. Moreover, the equipment presented here allows performing tests even in immersed conditions – not possible made with the inclined plane test. For the aforementioned reasons, it is believed that the direct shear equipment described here may find greater diffusion in the future and may allow further studies on the influence of the load application method, i.e. at a constant displacement speed or at a constant rate of loading.

Authors' contributions

Conceptualisation: P.P.; methodology: P.P.; data curation: P.P.; writing – original draft preparation: P.P. and P.C.; writing – review and editing: P.C. and N.M.; supervision: N.M.

All authors have read and agreed to the published version of the manuscript.

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OCENA OPORÓW TARCIA POMIĘDZY GEOSYNTETYKAMI PODCZAS WYSTĘPOWANIA MAŁYCH NAPRĘŻEŃ NORMALNYCH: PORÓWNANIE DWÓCH METOD BADAWCZYCH

STRESZCZENIE

Opory tarcia pomiędzy geosyntetykami przy średnich i dużych naprężeniach normalnych były przedmiotem wielu badań. Tarcie pomiędzy geosyntetykami w warunkach małych naprężeń normalnych jest zdecydowanie mniej rozpoznanym obszarem badawczym. Tymczasem opory tarcia pomiędzy geosyntetykami przy małych obciążeniach normalnych mają znaczący wpływ w przypadku barier geosyntetycznych na składowiskach odpadów. Do wyznaczenia kąta tarcia pomiędzy geosyntetykami przy naprężeniach normalnych równych 5 kPa powszechnie stosuje się metodę z wykorzystaniem równi pochyłej. Istnieje także możliwość wykorzystania aparatu bezpośredniego ścinania. Badania tego nie można jednak przeprowadzić przy małych wartościach naprężeń normalnych. W artykule przedstawiono wyniki badań przeprowadzonych z wykorzystaniem równi pochyłej oraz w aparacie pozwalającym na zadanie określonej wartości naprężeń. Uzyskane wyniki badań wskazują na możliwość wykorzystania w przyszłości innowacyjnych metod pomiaru oporu tarcia pomiędzy geosyntetykami.

Słowa kluczowe: geosyntetyki, opory tarcia, równia pochyła, bezpośrednie ścinanie