Studia Geotechnica et Mechanica, Vol. XXXV, No. 4, 2013
DOI: 10.2478/sgem-2013-0035

FRICTIONAL CHARACTERISTICS OF GEOSYNTHETIC–GEOSYNTHETIC AND GEOSYNTHETIC–SOIL INTERFACES DETERMINED BY THE INCLINED PLANE APPARATUS

DAMIAN RZEPECKI

Gdańsk (Poland)

JEAN-PIERRE GOURC

University Joseph Fourier, Grenoble (France), e-mail: gourc@ujf-grenoble.fr

EUGENIUSZ DEMBICKI

Gdańsk University of Technology, Gdańsk (Poland), e-mail: edemb@pg.gda.pl

Abstract: The problem of managing the unneeded and unusable materials is a serious challenge for modern societies. The progress of civilization is accompanied by an increase of the human population. This results in a constant increase of waste production. An average EU citizen generates over 500 kg of municipal waste per year, of which less than one third is recycled. The rest is either disposed of in the landfills or incinerated. Every landfill needs to be properly protected by an impermeable barrier – a liner. Its use is necessary to prevent soil and ground water contamination. The protection barrier needs to be implemented both at the bottom and at the top of a landfill. Various geosynthetic materials are utilized for a liner design. Waste disposed of in a landfill creates high embankments with steep slopes. In these conditions, the problem of liner stability arises. The tests, the results of which are presented in this paper, were conducted to analyze the behaviour of several different combinations of geosynthetic materials used for liner design and to calculate the friction angle of the interface between them. A set of combinations, crucial for the stability of a landfill capping system was tested: geomembrane–geospacer, geospacer–geotextile and geotextile–soil. All of the tests were conducted at the LTHE Laboratory at Joseph Fourier University in Grenoble, France.

1. INTRODUCTION

Every landfill needs to be properly protected by an impermeable barrier – a liner, its use is necessary to prevent soil and ground water contamination. The protection barrier needs to be implemented both at the bottom and the top of landfill.

Various geosynthetic materials are utilized for a liner design. Waste disposed in a landfill creates high embankments with steep slopes. In these conditions, the problem of liner stability arises. The tests, the results of which are presented in the subsequent part of this paper, were conducted to analyse the behaviour of several different combinations of geosynthetic materials used for liner design and to calculate the friction angle of the interface between them. A set of combinations crucial for the stability of a landfill capping system was tested: geomembrane–geospacer, geospacer–geotextile and geotextile–soil. Furthermore, a series of tests on combinations not used in landfill designs (geomembrane–geotextile) but utilized in many other geotechnical applications, were carried out.

All of the tests were conducted at the LTHE laboratory at Joséph Fourier University in Grenoble, France (JFU).

2. GEOSYNTHETIC LINING SYSTEM

The Geosynthetic Liner System (GLS) design is based on the separation of the different functions. The main components are a geomembrane (for sealing), a geospacer (for water drainage), a geotextile (for filtration of larger particles to avoid clogging of the geospacer) and a 20–50 cm thick veneer cover soil layer (for protection). When considering stability of the GLS, we need to focus on the interfaces between the separate parts of a lining system. The normal stress applied on the GLS at the landfill site is often low ($\sigma_n' < 10$ kN). The sources of this stresses are primarily the weight of the protective soil layer and the traffic during site construction. A number of experiments have been carried out to determine the best type of equipment for characterizing the behaviour of geosynthetic–soil interface at low stress (Izgin and Wasti 1998; R. Ramirez and J.-P. Gourc 2003, Lala Rakotson (1998); Wasti and Özdüzgün 2001). The authors tested two devices: a great shear box (Fig. 1) and a inclined plane. The results of tests discussed in the above-mentioned papers indicate that the inclined plane appa-

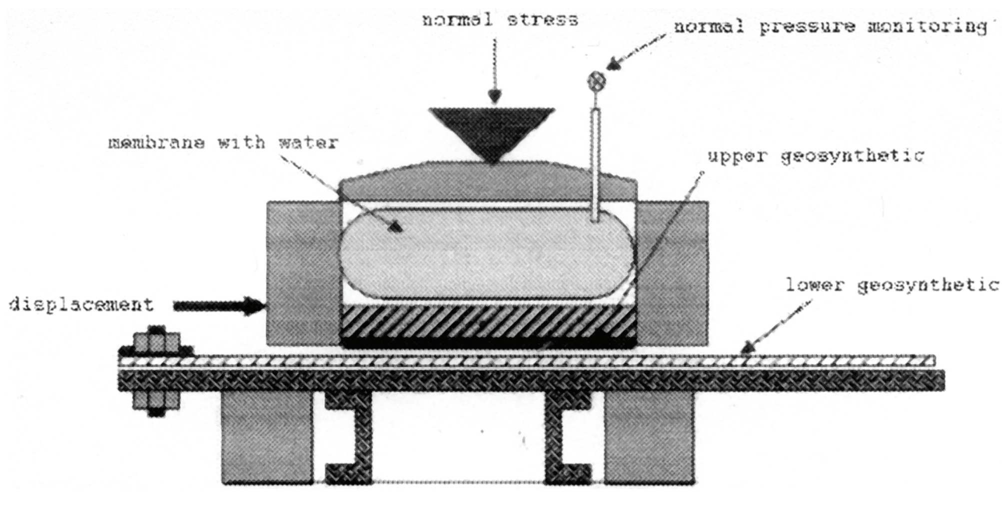

Fig. 1. Shear box device adapted to geosynthetic–geosynthetic interface tests

ratus is more suitable for the needs of geosynthetic–soil interface characterization since the shear box is not sensitive to low stress values. Another advantage of the inclined plane is its adaptability. After some changes in the equipment not requiring much physical work, it is possible to carry out tests with combinations of geosynthetic–geosynthetic samples.

3. INCLINED PLANE

The inclined plane device is specially designed for tests on soil–geosynthetic surface. Its basic elements are:

- the rigid support plate-sloping platform;
- tilting system: a motor, guiding poles, a variator (Fig. 2);
- a displacement monitoring device (Fig. 3);
- a soil retaining box (Fig. 4).

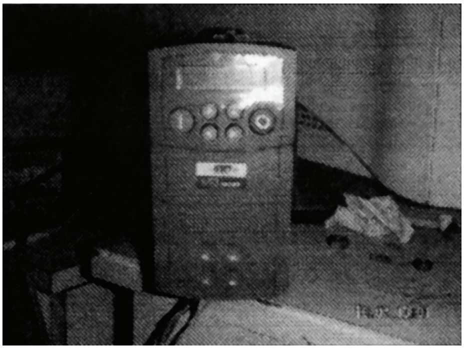

Fig. 2. The variator

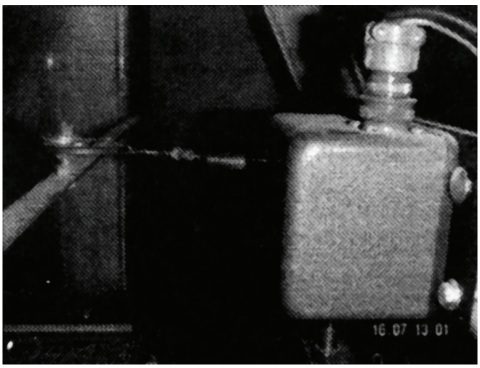

Fig. 3. The displacement monitoring device

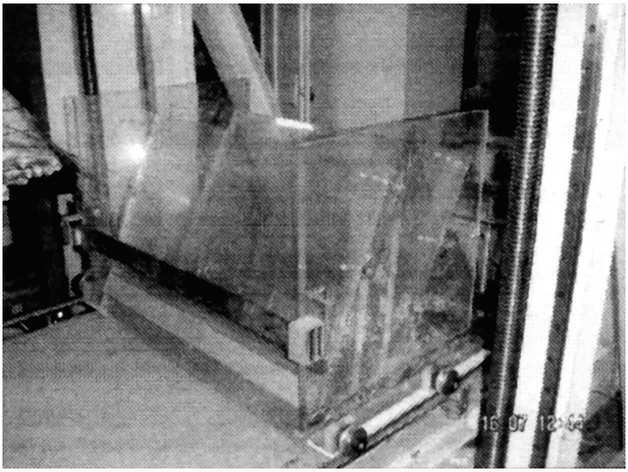

Fig. 4. The soil retaining box

During the tests, a geosynthetic sample (0.80 m × 1.3 m) is bound to the top of the sample and filled with desired amount of soil. The charge (a steel plate) is then placed in the box to provide the normal initial stress σ'_o. The box is connected to the displacement measuring device (Fig. 5). As the inclination angle grows, the soil retaining box begins to slide down the platform. The guiding poles fixed to the rigid support plate assure straight movement of the box. The interface between the box's wheels and the guiding poles is assumed to be frictionless.

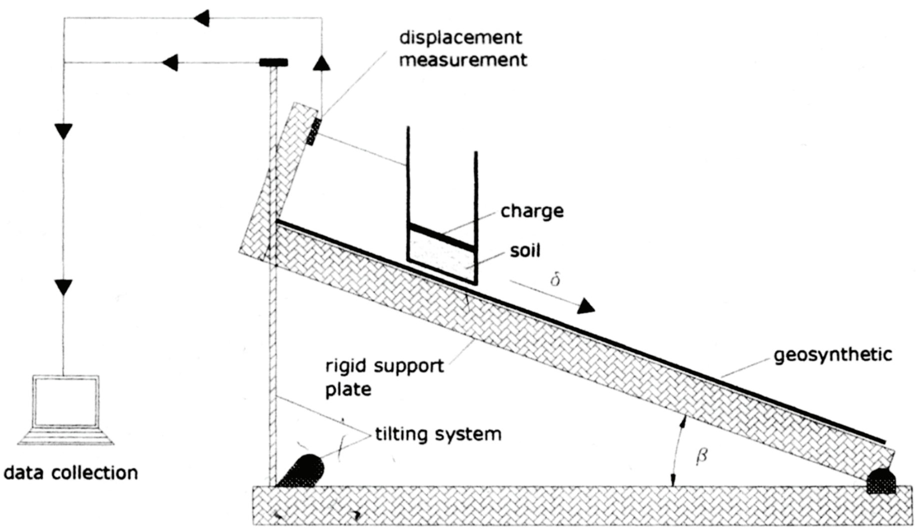

Fig. 5. General conditions of soil–geosynthetic interface test

The whole equipment is connected to as computer system that registers data sent from the sensors (inclination angle, displacement) as well as the time of test and saves it into an "xls" file format.

The file can be easily opened and edited using popular software (i.e., MS Office, OpenOffice.org).

3.1. ADAPTATION OF THE INCLINED PLANE TO GEOSYNTHETIC–GEOSYNTHETIC INTERFACE TESTS

For the needs of these tests the inclined plane device undergoes very few changes (Fig. 6). The main and the most significant change is that the soil retaining box is replaced by a wooden plate (0.70 m × 0.18 m) to which a geosynthetic sample had been glued. Next, the initial normal stress ($\sigma'_o = w/s$), where w includes the weight of the wooden plate, is applied using the metal support plate as an overload. Additional plates can be added for an increased normal stress value. The guides on the metal support plate assuring straight movement are assumed to be frictionless.

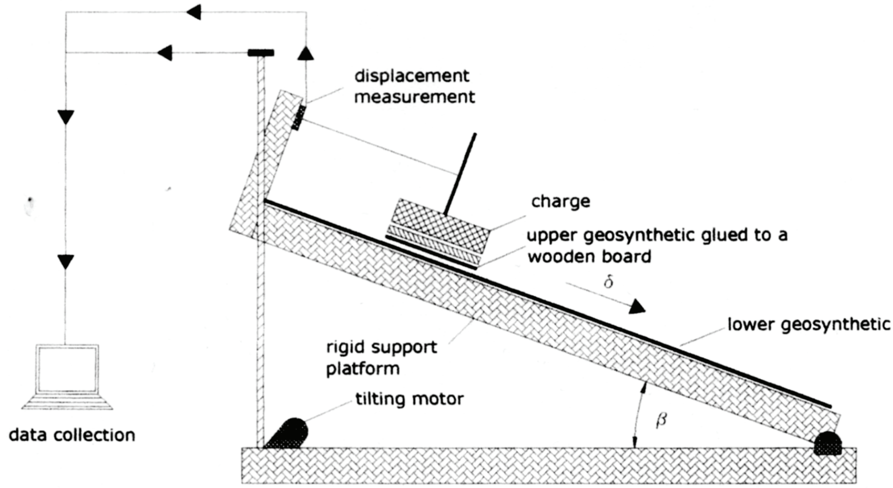

Fig. 6. General conditions of geosynthetic–geosynthetic interface test

4. GEOSYNTHETIC–GEOSYNTHETIC INTERFACE TESTS

4.1. INTRODUCTION

There is no inclination in the initial state of the inclined plane ($\beta = 0$) and the interface of the geosynthetic samples is submitted to a normal stress σ'_o. The rigid support platform is inclined at a constant rate of 3 degrees per minute ($d\beta/dt$ = 3°/min) until reaching the non-stabilized angle (β_s). At $\beta = \beta_s$ the sample slides down to the bottom of the inclined plane. During the test, the effective normal stress acting on the surface decreases constantly ($\sigma' = \sigma'_o\, x\, \cos\beta$). The guidance of the metal support is assumed to be frictionless. The angle of interface friction (β_{gg}) is assumed to be equal to the non-stabilized sliding angle (β_s) (Gourc, Pitanga et al. 2006). In accordance with the European standard (EN ISO 12957-2, 2001), this parameter is calculated for a 50 mm displacement (δ = 50 mm).

The course of the IP test is not homogenous (Gourc, Pitanga et al. 2004), three phases with distinguished (Fig. 7).

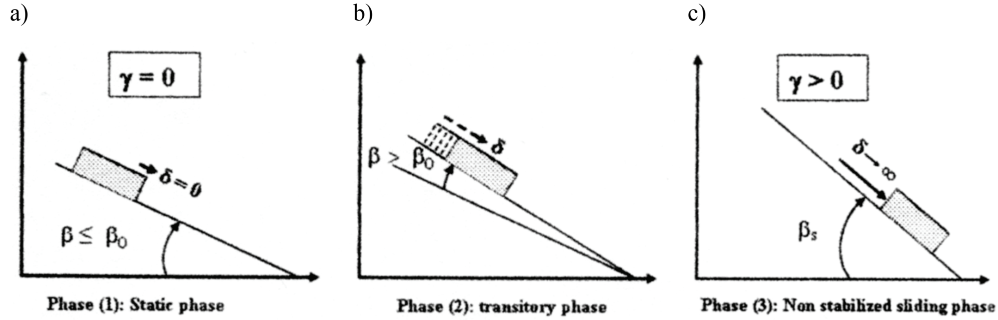

Fig. 7. Different phases of the upper plate movement, for an increasing inclination of the inclined plane; (a) Phase 1, static phase; (b) Phase 2, transitory phase; (c) Phase 3, non-stabilized sliding phase

- Phase 1 (static phase); the upper sample practically immobile (δ = 0) until reaching an angle $\beta = \beta_o$;
- Phase 2 (transitory phase) for an increasing inclination ($\beta > \beta_o$), the upper sample moving gradually downwards;
- Phase 3 (non-stabilized sliding phase); the upper sample undergoes non-stabilized sliding at an increasing speed even if plane inclination is held constant ($\beta = \beta_s$).

The displacement key value is δ = 50 mm. However Phase 2 (transitory phase) very often occurs for a lesser than 50 mm displacement. Furthermore, when testing geosynthetic–geosynthetic interfaces. Phase 2 does not exist in most cases and the sample starts the non-stabilized sliding immediately after Phase 1.

4.2. GEOSYNTHETIC MATERIAL USED

In the tests conducted, several different geosynthetic materials have been used (Table 1). Various combinations of test materials are listed in Table 2. Either a high density polyethylene geomembrane (HDPEgm) or a high density polyethylene geospacer (gs6) has been used as the lower geosynthetic. The geospacers were of the same shape concept but their thickness was different (Fig. 8).

Table 1

List of geosynthetics used in the IP tests

	Type of geosynthetic	Material	Test notation	Thickness (mm)
1	Geomembrane	HDPE	HDPEEgm	1.5
2	Geomembrane	PVC	PVCgm	0.75
3	Geospacer	HDPE	gs6	6
4	Geospacer		gs8	8
5	Geotextile	polypropylene	gtx	2
6	Geotextile		gtxR	2.5
7	Geotextile	polyester	gtxRblack	1.5
8	Geotextile		gtxRblue	1.5

Table 2

Various combinations of geosynthetics tested

	Lower geosynthetic (test notation)	Upper geosynthetic (test notation)
1	HDPEgm	gs6
		gs8
2	gs6	gtx
		gtxR
		gtxRblack
		gtxRblue
		PVCgm

Fig. 8. The geospacers

The following materials have been used as the upper geosynthetic:
1. non-woven non-reinforced geotextile – gts (Fig. 9);
2. non-woven geotextile, reinforced with polyester fiber – gtxR (Fig. 10);
3. woven geotextile, reinforced with black polyester fiber – gtxRblack (Fig. 11);
4. woven geotextile, reinforced with blue polyester fiber – gtxRblue (Fig. 12);
5. geospacer – gs6 (Fig. 8);
6. geospacer – gs8 (Fig. 8);
7. geomembrane – PVCgm

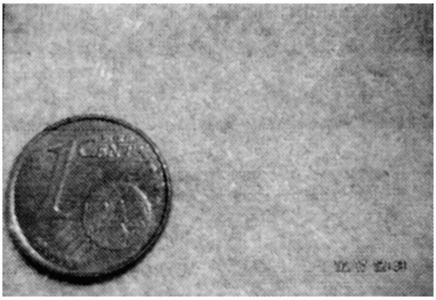

Fig. 9. Macro view of the gtx

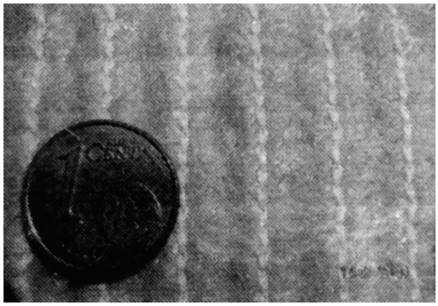

Fig. 10. Macro view of the gtxR

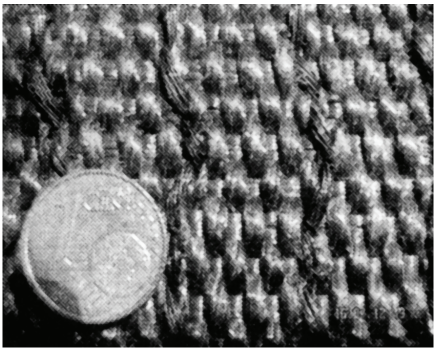

Fig. 11. Macro view of the gtxRblack

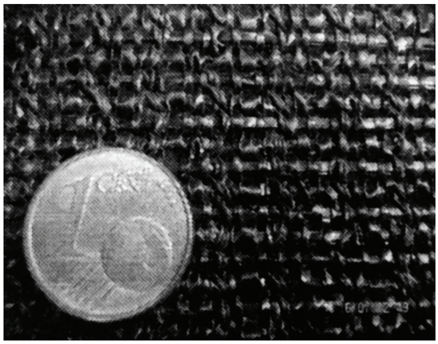

Fig. 12. Macro view of the gtxRblue

4.3. CHARGE

To provide the required normal stress, two metal plates were used, 10 kg each. Their weight was combined with the weight of the metal support plate (30 kg) and the weight of the wooden plate (1 kg) to which the geosynthetic sample had been glued. They summed up to the total weight of 51 kg. Given the dimensions of the wooden plate (0.70 m × 0.18 m = 0.126 m^2), the normal stress acting on the interface was 4.0 kPa

$$\sigma'_o = \frac{51\,\mathrm{kg} \cdot 9.81 \frac{\mathrm{m}}{\mathrm{s}^2}}{0.126\,\mathrm{m}^2} = 3970.71\,\mathrm{Pa} \cong 4.0\,\mathrm{kPa}\,.$$

Every geosynthetic–geosynthetic interface test was conducted with the same value of normal stress acting on the interface.

4.4. TEST COURSE

Before starting every test the inclined plane was reset ($\beta = 0$). After resetting the super geosynthetic sample was put in an initial position ($\delta = 0$, position A, Fig. 13) and the desired normal stress was applied using metal plate. The lower geosynthetic was already fixed to the lower platform. After having prepared everything the test started. The base platform was inclined at a constant rate ($\mathrm{d}\beta$ / $\mathrm{d}t$ = 3°/min) until obtaining the non-stabilized sliding angle (β_s). When the upper plate slid to the bottom of the inclined plane, the apparatus was stopped. During the test a computer system connected to the IP was constantly monitoring the changing of time, displacement and inclination angle.

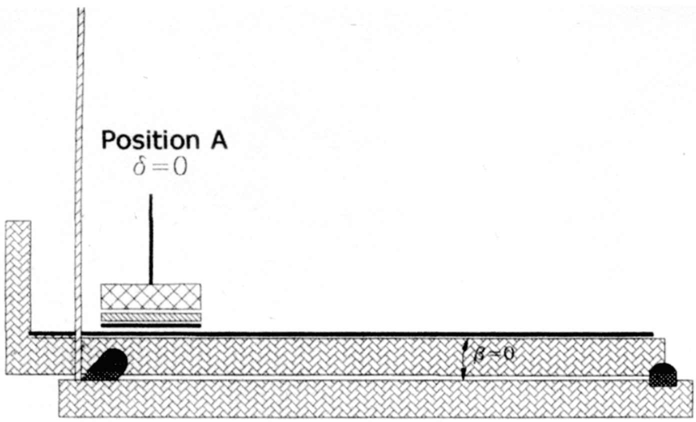

Fig. 13. IP prepared for a test

5. PRESENTATION OF TEST RESULTS

Every test was repeated several times in order to gain credible results and to exclude possible errors. The most representative results were selected for discussion and will now be shortly presented.

Fluctuation of the curves visible in some of the diagrams is a result of the inaccuracy of the registering equipment.

5.1. HDPEgm AS THE LOWER GEOSYNTHETIC

These two tests were carried out with high density polyethylene geomembrane (HDPEgm) as the lower sample and one of two types of high density polyethylene geospacer as the upper sample (gs6 or gs8, Fig. 14).

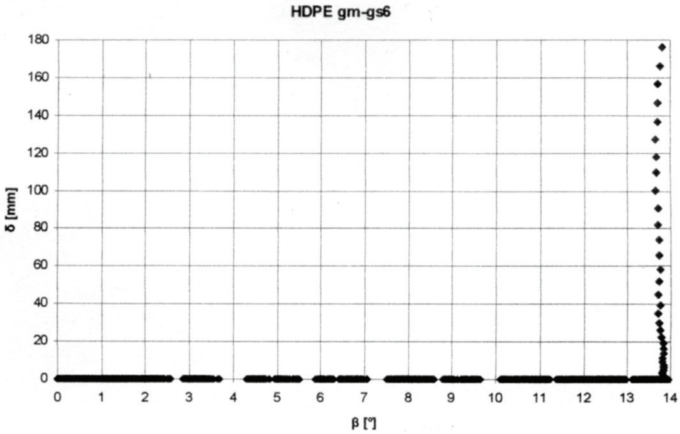

Fig. 14. HDPEgm–gs6 interface test

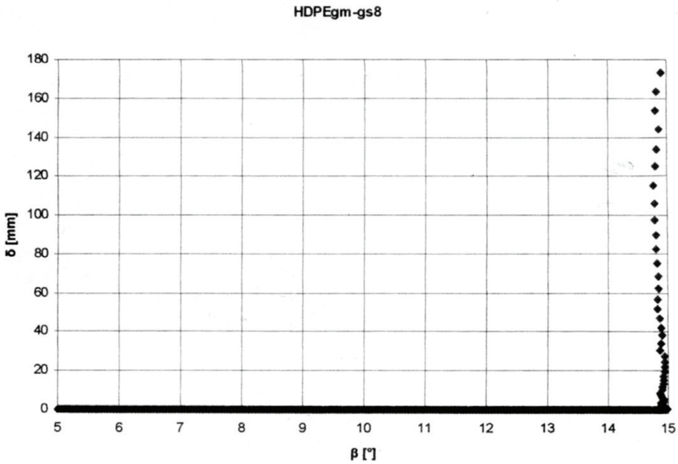

Fig. 15. HDPEgm–gs8 interface test

Test 1. HDPEgm–gs6 interface (Fig. 14). At can be observed from the diagram, the upper sample remains in Phase 1 (static phase) for the most part of the test. When the inclination reaches an angle $\beta = 13.8°$, the upper sample moves into Phase 3 (non-stabilized sliding). Phase 2 is practically non-existent. At the 50 mm displacement the friction angle is about 0.1° smaller than $\beta = \beta_s$. Since the inclination continued to rise, most likely the fault lies in the equipment's inaccuracy. The friction angle for HDPEgm-gs6 interface under the initial stress σ'_o = 4.0 kPa is ϕ_{gg} = 13.8°.

Test 2. HDPEgm–gs8 interface. At can be observed from the diagram in Fig. 15, changing the geospacer (gs6) for a bigger one (gs8) affects the friction angle. The course of the test remains similar to the previous one. Again, Phase 2 is practically non-existent. After reaching the inclination angle $\beta = \beta_s$ = 14.9°, the upper sample almost immediately begins the non-stabilized sliding.

The friction angle for HDPEgm-gs8 interface under the initial stress σ'_o = 4.0 kPa is ϕ_{gg} = 14.9°.

5.2. GS6 AS THE LOWER GEOSYNTHETIC

These five tests were carried out with a high density polyethylene geospacer (gs6) as the lower sample. The upper sample was either one of the four different polyester geotextiles (gtxR, gtxRblack, gtxRblue) or a polyvinyl chloride geomembrane (PVC gm). The initial normal stress on the interface was the same as in the previous tests (σ'_o = 4.0 kPa).

1. Test 3: gs6–gtx interface

In this test, the upper sample is non-woven, non-reinforced geotextile. The course of the test is identical to the previously conducted ones, with dominating Phase 1 and insignificant Phase 2. The non-stabilizing sliding begins when the inclination reaches the angle $\beta = \beta_s$ = 12.4° (Fig. 16).

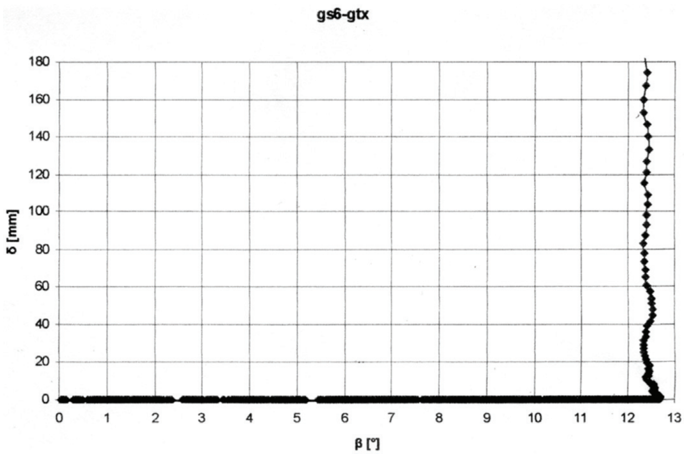

Fig. 16. gs6–gtx interface test

The friction angle for gs6–gtx interface under the initial stress σ'_o = 4.0 kPa is ϕ_{gg} = 12.4°.

2. Test 4: gs6–gtxR interface (Fig. 17).

In this test, the upper sample is non-woven geotextile, reinforced with polyester fiber. The diagram (Fig. 17) shows that the non-stabilized sliding begins when the inclination reaches the angle $\beta = \beta_s = 12.7°$. The friction angle for gs6–gtxR interface under the initial stress $\sigma'_o = 4.0$ kPa is $\phi_{gg} = 12.7°$.

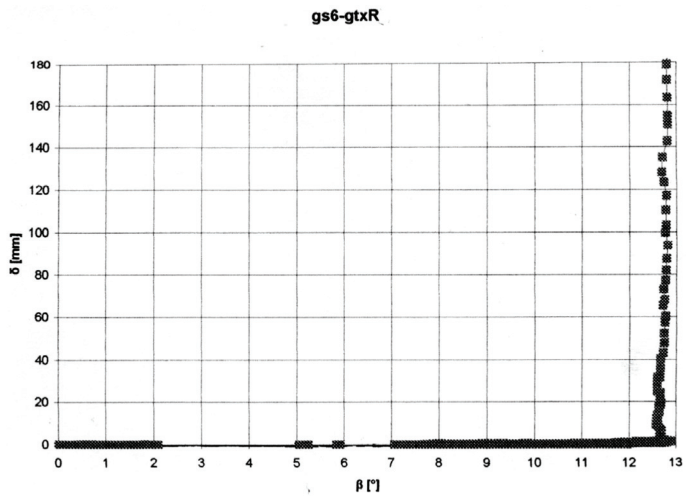

Fig. 17. gs6–gtxR interface test

3. Test 5: gs6–gtxRblack interface.

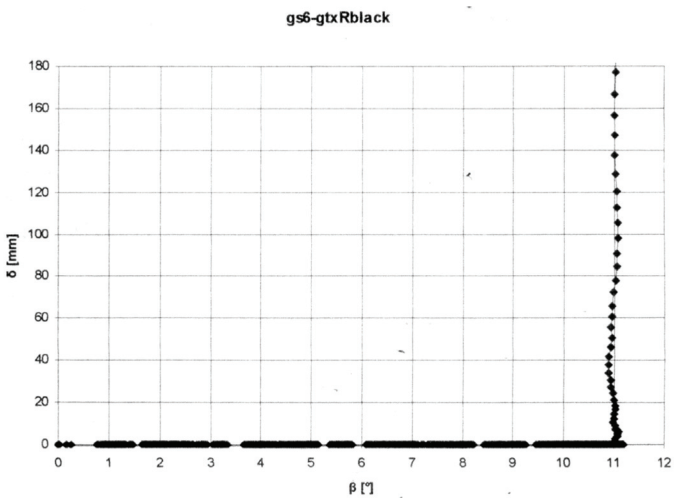

Fig. 18. gs6–gtxRblack interface test

The upper sample in this test is woven geotextile, reinforced with polyester fiber. The non-stabilized sliding begins when the inclination reaches the angle $\beta = \beta_s$ = 11.1° (Fig. 18). The friction angle for gs6R block interface under the initial stress σ'_o = 4.0 kPa is ϕ_{gg} = 11.1°.

4. Test 6: gs6–gtxRblue interface

The upper sample in this test is a different type of woven geotextile, reinforced with polyester fiber. The diagram (Fig. 19) shows that the non-stabilized sliding begins when the inclination reaches the angle $\beta = \beta_s$ = 9.3°. The friction angle for gs6–gtxRblue interface under the initial stress σ'_o = 4.0 kPa is ϕ_{gg} = 9.3°.

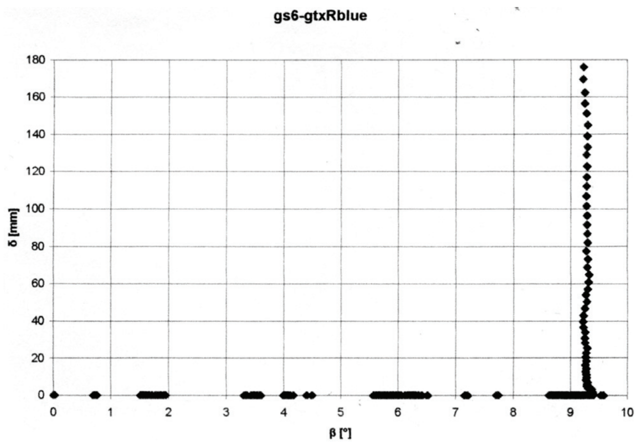

Fig. 19. gs6–gtxRblue interface test

5. Test 7: gs6–PVCgm interface

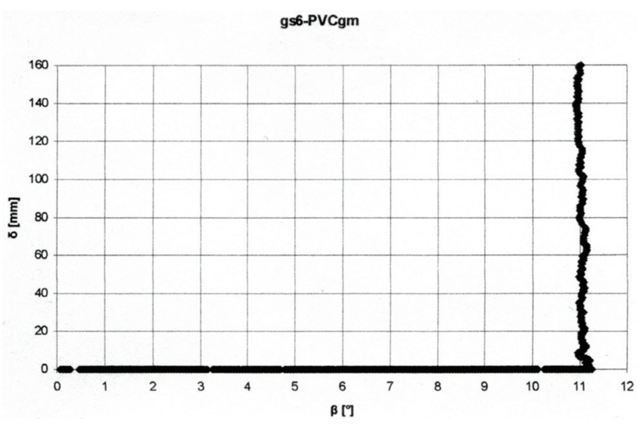

Fig. 20. gs6–PVCgm interface test

In this test, the upper sample is polyvinyl chloride geomembrane. We can see on the diagram (Fig. 20) that Phase 3 of the movement starts when the inclined plane reaches the angle $\beta = \beta_s = 11.0°$. The friction angle for gs6–PVCgm interface under the initial stress $\sigma'_o = 4.0$ kPa is $\phi_{gg} = 11.0°$.

5.3. TEST RESULTS – COMPARATIVE ANALYSIS AND DISCUSSION

Several different geosynthetic materials were tested. At can be observed from the diagrams each of them displays different frictional characteristics. Friction angles required from the test are listed in Table 3.

Table 3

Geosynthetic–geosynthetic interface friction test results

	Lower geosynthetic (test notation)	Upper geosynthetic (test notation)	Test number	Friction angle ϕ (°)
1	HDPEgm	gs6	1	13.8
		gs8	2	14.9
2	gs6	gtx	3	12.4
		gtxR	4	12.7
		gtxRblack	5	11.1
		gtxRblue	6	9.3
		PVCgm	7	11.1

5.3.1. HDPEgm–gs6/gs8 INTERFACE

The best two interfaces tested were between geomembrane and the two different geospacers. As expected, the friction angle (ϕ_{gg}) calculated from HDPEgm–gs6 interface test is different from the one calculated from HDPEgm–gs8 interface test. Changing the geospacer for a larger one results in a significant (1.2°) increase in the friction angle. Thus, considering only the friction angle, using gs8 is suggested when designing a Geosynthetic Lining System.

5.3.2. gs6–gtx/gtxR INTERFACE

Tests numbered from 3 to 6 were between the smaller geospacer (gs6) and four geotextiles. Geotextiles used in these tests can be divided into two pairs non-woven (gtx, gtxR) and woven (gtxRblack, gtxRblue). The friction angle calculated for gs6–gtx interface is $\phi_{gg} = 12.4°$. The implementation of reinforcement into this type of geotextile resulted in a 0.3° increase of the friction angle – the friction angle for gs6–gtxR interface is $\phi_{gg} = 12.7°$. Such small increase is negligible when calculating the stability of a GLS.

5.3.3. gs6–gtx/gtxRBLACK/ gtxRBLUE INTERFACE

In the fifth test, the upper sample was woven reinforced geotextile (gtxRblack). The friction angle for gtxRblack is ϕ_{gg} = 11.1°. Compared to the previous non-woven geotextiles (either non-reinforced or reinforced), a large decrease of the friction angle is clearly visible: 1.3° when considering the first one, 1.6° when considering the second one. The second woven reinforced geotextile (gtxRblue) of the same structural concept but of a different type and characteristics. This became obvious after the test was accomplished. The friction angle for gtxRblue is ϕ_{gg} = 11.1°. Further significant decrease of the friction angle is observed in this case.

After comparing the results obtained from tests on geospacer–geotextile interfaces, the conclusion is that the non-woven reinforced geotextile (gtxR) is the most suitable one for a Geosynthetic Lining System, since the friction angle for gs6–gtsR interface is the highest (ϕ_{gg} = 12.7°). However, when designing a GLS many factors need to be taken into account not only the interface friction angle. For example, the problem of rupture of the geosynthetic on slope resulting in a global failure of a GLS is a serious issue. When focusing on this problem, the woven geotextiles have definitely better characteristics than non-woven ones. That is why thorough examination of the stability of a GLS problem is a key matter.

5.3.4. gs6–PVCgm INTERFACE

The last interface tested was between HDPE geospacer and PVC geomembrane. Compared to the previously tested interface of HDPE geomembrane and HDPE geospacer, a considerable decrease (2.7°) in the friction angle is observed. However, in this test the samples are switched – now, the geomembrane is glued to the moving wooden plate, unlike in the HDPEgm–gs6 interface test. But according to (Gourc, Pitanga et al. 2004), where a similar situation was observed, this exchange should result in a noteworthy increase of the friction angle as well as in the change in the Phase 2 of the test – sliding of the sample should change from sudden to gradual. Yet in this instance this is not the case. Once again Phase 2 is practically non-existent and the sample starts the non-stabilized sliding immediately after reaching an angle $\beta = \beta_s$ = 11.1°.

6. GEOSYNTHETIC–SOIL INTERFACE TESTS

The geosynthetic–soil interface tests required a small charge in the equipment: the wooden plate to which the upper geosynthetic sample had been glued was replaced with the soil retaining box. Once again we assume there is no friction on the interface between the guiding poles and the box's wheels.

The course of the test was not identical to the course of dual geosynthetic interface test. In geosynthetic–soil interface tests, all of the three phases mentioned before are present. This time Phase 2 is very clear and easy to observe.

The sequence of actions performed during an inclined plane test remains exactly the same as before.

6.1. TEST MATERIALS

1. Soil

The soil commonly used on cap covers of landfills is sandy sand a 4 cm layer of silt, with the 6% water content was used.

2. Geosynthetics

Stability of the protective veneer soil layer is a difficult problem. To improve it, geosynthetic manufacturers developed a new product – geotextile reinforced with geomat. Two products of this type were tested and one without reinforcing geomat:

- Polypropylene woven geotextile TERRALYS LF 75/7511 (gtxLF, Fig. 21);
- Polypropylene woven geotextile reinforced with geomat HP 75/75L-L (gtxHP, Fig. 22);
- Polypropylene woven geotextile reinforced with geomat (gtxMat, Fig. 23).

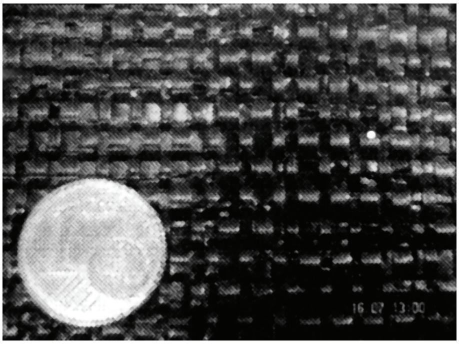

Fig. 21. Macro view of gtxLF

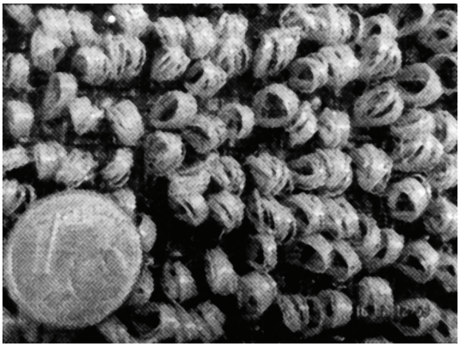

Fig. 22. Macro view of gtxHP

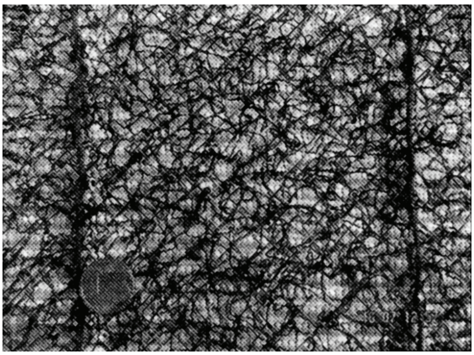

Fig. 23. Macro view of gtxMat

3. Charge

Two low values of normal stress were employed in geosynthetic–soil interface tests: 2.0 kPa and 2.2 kPa. The value of the normal stress was the sum of soil's weight and the weight of one of two metal plates (15 kg and 20 kg).

For the lower stress value: 0.4 kPa (soil) + 1.6 kPa (plate) = 2.0 kPa.

For the higher stress value: 0.4 kPa (soil) + 1.8 kPa (plate) = 2.2 kPa.

6.2. PRESENTATION OF TEST RESULTS

Each of the interfaces was tested several times with one of two normal stress values acting on the interface. The most representative results were chosen for discussion.

6.2.1. NORMAL STRESS 2.0 kPA

1. Test 1: gtxLF–silt interface

The first interface tested was between silt and gtxLF – geosynthetic lacking reinforcement of a geomat. We can clearly observe from the diagram (Fig. 24) that there is Phase 2 in the sample (soil) movement. When the inclination reaches the angle β = 10.3° and lasts until the angle β = 10.9° is reached. After this point the movement becomes non-stabilized. The friction angle for gtxLF–silt interface under the initial stress σ'_o = 2.0 kPa is ϕ_{gs} = 10.9°.

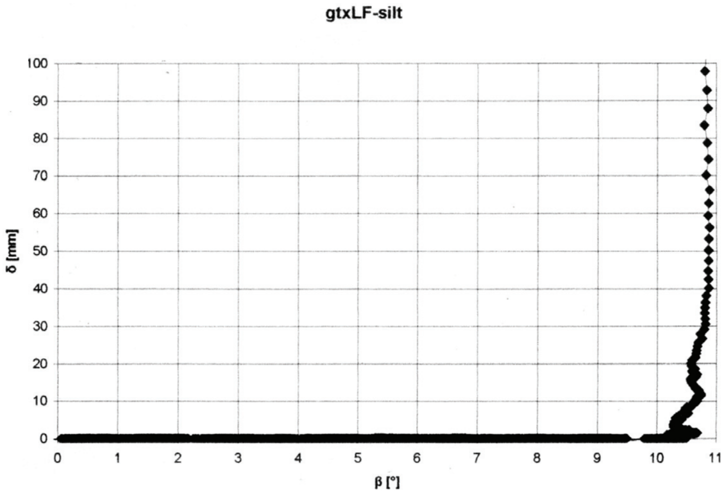

Fig. 24. gtxLF–silt interface test (2.0 kPa)

2. Test 2: gtxHP–silt interface

GtxHP is very similar to gtxLF. The difference lies in the addition of a reinforcing geomat. As expected, this reinforcement resulted in a large increase in the friction angle. The movement starts at the angle β= 11.7°. Phase 2 is very long in this test. When the inclination reaches the angle β = 16.2°, the sample starts non-stabilized sliding. The friction angle for gtxHP–silt interface under the initial stress σ'_o = 2.0 kPa is ϕ_{gs} = 16.2° (Fig. 25).

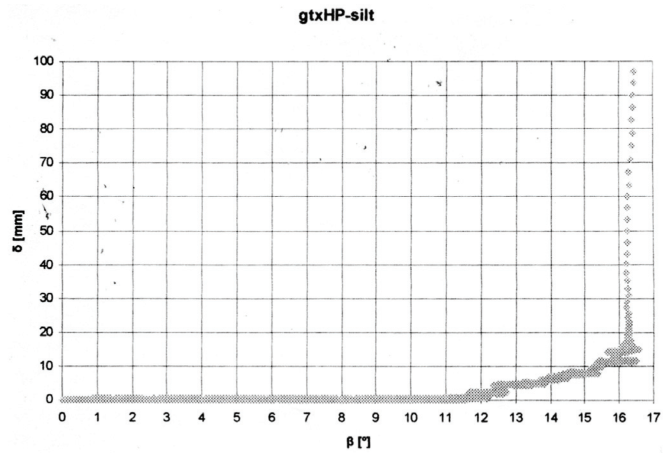

Fig. 25. gtxHP–silt interface test (2.0 kPa)

3. Test 3: gtxMat–silt interface

The third test was carried out using gtxMat. A very clear Phase 2 can be observed from the diagrame in Fig. 26. The movement starts at the angle β= 16,7°. It lasts for about 90 seconds (4.6°). Non-stabilized movement (Phase 3) starts when β= 21.3°. The friction angle for gtxMat–soil interface under the initial stress σ'_o = 2.0 kPa is ϕ_{gs}= 21.3°.

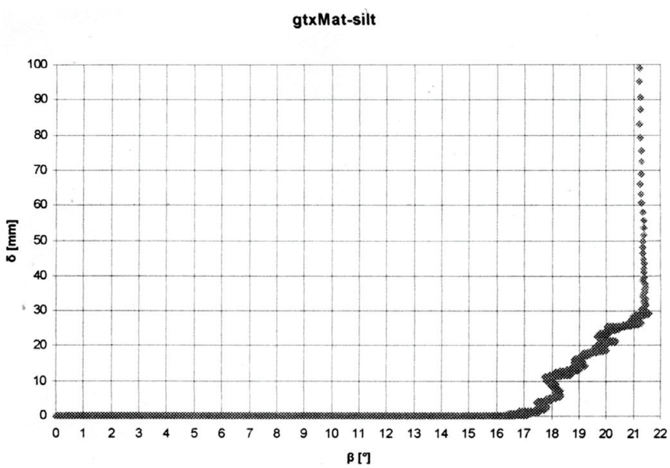

Fig. 26. gtxMat–silt interface test (2.0 kPa)

6.2.2. NORMAL STRESS 2.2 kPA

The sequence of tests in this part of the testing program was identical to the one that was previously followed. The only difference was a higher normal stress applied to the interface.

1. Test 4: gtxLF–silt interface

The fourth test was carried out using gtxLF. A change in the movement can be observed from the diagram (Fig. 27), namely the lack of Phase 2. When the inclination reaches the angle β = 11.6°, the sample immediately starts non-stabilized movement. The friction angle for gtxFL–silt interface under the initial stress σ'_o = 2.2 kPa is ϕ_{gs} = 11.6°.

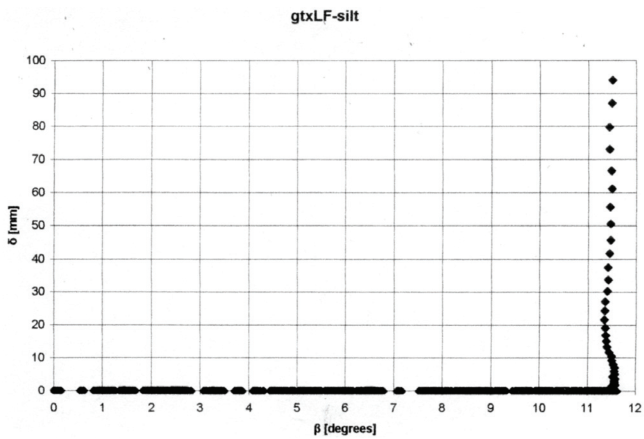

Fig. 27. gtxLF–silt interface test (2.2 kPa)

2. Test 5: gtxHP–silt interface

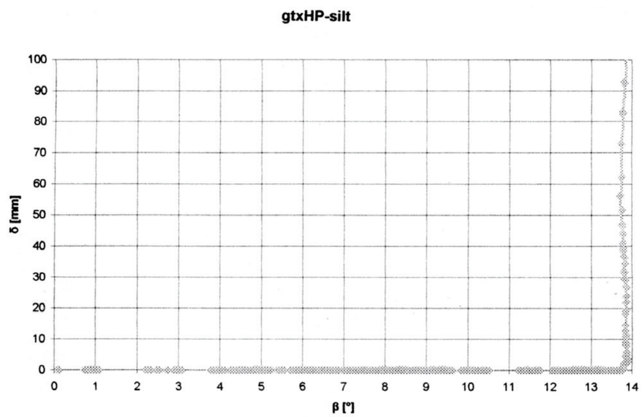

Fig. 28. gtxHP–silt interface test (2.2 kPa)

GtxHP was utilized in the fifth test. Just like in the previous test the lack of Phase 2 is visible from the diagram (Fig. 28). The non-stabilized movement begins when the inclination reaches the angle $\beta = 13.9°$. The friction angle for gtxHP–silt interface under the initial stress $\sigma'_o = 2.2$ kPa is $\phi_{gs} = 13.9°$.

3. Test 6: gtxMat–silt interface

The last geosynthetic tested was gtxMat. Contrary to the previous test, Phase 2 is present in this one, but it is significantly shorter. It starts at the inclination angle $\beta = 17.7°$ and stops at $\beta = 18.4°$ (Fig. 29). The friction angle for gtxMat–silt interface under the initial stress $\sigma'_o = 2.2$ kPa is $\phi_{gs} = 18.4°$.

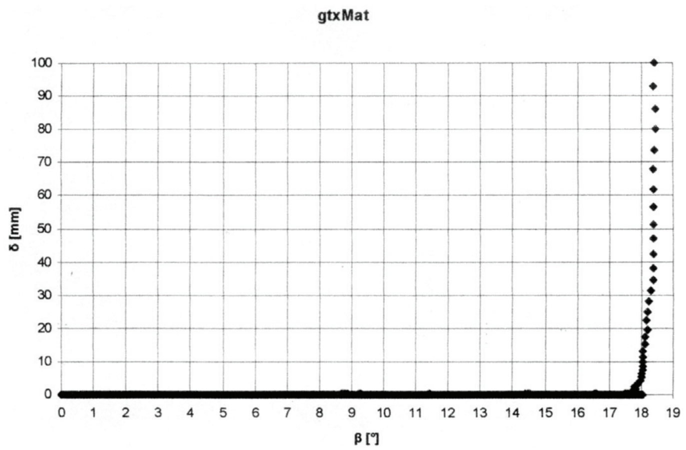

Fig. 29. gtxMat–silt interface test (2.2 kPa)

6.3. TESTS RESULTS – DISCUSSION AND COMPARATIVE ANALYSIS

6.3.1. NORMAL STRESS: 2.0 kPA

The results of the tests on geosynthetic–silt interfaces under the initial stress $\sigma'_o = 2.0$ kPa are illustrated in the diagram in Fig. 30. As presumed the product without the reinforcement of geomat has a significantly lower friction angle than the other two. The friction angle for gtxLF–silt interface is $\phi_{gs} = 10.9°$. Addition of a geomat to this geosynthetic resulted in the friction angle $\phi_{gs} = 16.2°$. The last geosythetic tested reached the friction $\phi_{gs} = 21.3°$. It is safe to say that adding geomat to geosynthetic results in a significant increase in its soil-retaining properties. However, the first movement starts long before the actual friction angle, which is calculated for a 50 mm displacement. This means that what actually assures higher friction angles is the presence of a long Phase 2. The gradual sliding prolongs the time before the inevitable non-stabilized sliding.

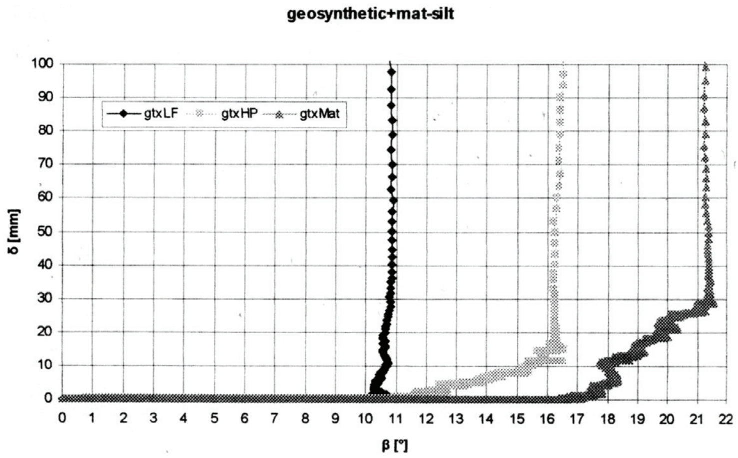

Fig. 30. Geosynthetic+mat–silt interface test (2.0 kPa)

6.3.2. NORMAL STRESS: 2.2 kPA

The diagram in Fig. 31 illustrates the results of the tests on geosynthetic–silt interfaces under the initial stress σ'_o = 2.2 kPa. Previous research indicated that the friction angle decreases, with increasing normal stress applied to the interface (Gourc and Pitanga, 2007). During our tests, we observed that even a small change in the value of the normal stress (0.2 kPa increase in this case) influences the results. But the value of the friction angle is not the only thing that was affected. In the first two tests, the behaviour of the sample changes as well: Phase 2 is no more present in these tests and the non-stabilized sliding begins immediately after Phase 1.

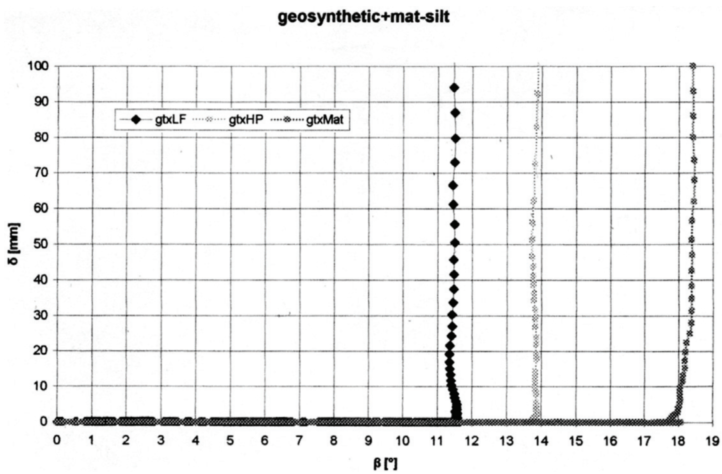

Fig. 31. Geosynthetic+mat–silt interface test (2.2 kPa)

The performance of the different geosynthetics remained adequate to the performance under the lower normal stress: ϕ_{gs} = 11.6° for gtxLF–silt interface ϕ_{gs} = 13.9° for gtxHP – silt interface and ϕ_{gs} = 18.4° for the interface between silt and gtxMat. The last material tested once again seems to be most suitable for a landfill capping application.

7. SUMMARY

The stability of a Geosynthetic Lining System is a complex matter. The particular interfaces prone to failure are specified in the second Section of this research. In the field conditions, these interfaces are subjected to low values of normal stress. That is why the Shear Box is not an appropriate device for studying the problem of the slope stability of geosynthetic systems, since it can provide only high normal stress values. When dealing with conditions of low normal stress values, the inclined plane apparatus is commonly used because it provides more reliable results.

The subject of this research was to compare the performance of several different geosynthetics applicable to a landfill design. Tests on dual geosynthetic interfaces as well as on soil–geosynthetic interfaces have been carried out. This initial normal stress employed in dual geosynthetic interface tests was σ'_o = 4.0 kPa. For the geosynthetic–soil interface tests, two values of normal stress were provided: σ'_o = 2.0 kPa and σ'_o = 2.2 kPa.

The tests on geomembrane–geospacer interfaces proved the larger geospacer (gs 8) to be better for landfill application. It achieved a 1.1° higher friction angle than gs6. The geomembrane–geotextile interface tests indicated that the best type of material for a Geosynthetic Lining System is the non-woven reinforced geotextile (gtxR), since its friction angle is highest ϕ_{gs} = 12.7°. The difference between gtxR and the other samples used in these tests is very significant and equals 3.4°.

The geosynthetic–soil interface tests were carried out in order to assess the influence of an addition of geomat to the woven geotextile, proposed by several manufacturers. The conclusion is that this addition does indeed significantly improve the frictional performance of the woven geotextile. The friction angle for the interface between the woven geotextile (gtxLF) and silt is ϕ_{gs} = 10.9° and for the gtxHP–silt interface it is ϕ_{gs} = 16.2°.

The tests were conducted with two values of normal stress that differ only slightly. The results of the tests showed that even a value of 0.2 kPa has a noticeable influence on the value of the friction angle.

The friction angles under the initial normal stress for gtxLF–silt and gtxHP–silt interfaces are ϕ_{gs} = 11.6° and ϕ_{gs} = 13.9°. As expected higher value of the normal stress – lowered the friction angle for gtxHP–silt interface. For gtxLF–silt interface the friction angle increased by 0.7°.

It should be mentioned that the utmost caution was undertaken to assure reliability of test results. However, it is practically impossible to recreate identical test conditions, so every test was repeated several times in order to gain credible results.

REFERENCES

[1] GOURC P., PITANGA H.N., REYES RAMIREZ R., JAROUSSEAU C., *Questions raised regarding interpretation of inclined plane results for geosynthetics interfaces*, 2006.
[2] GOURC P., REYES RAMIREZ R., VILLARD P., *Assessment of Geosynthetics Interface Friction for Slope Barriers of Landfill*, 2004.
[3] IZGIN M., WASTI Y., *Geomembrane – sand interface frictional properties as determined by inclined board and shear box tests*, Geotextiles and Geomembranes, 19 (2001), 45–47.
[4] REYES RAMIREZ R., GOURC J.P., *Use of the inclined plane tests in measuring geosynthetic interface friction relationship*, Geosynthetic International, 2003.
[5] RZEPECKI D., *Frictional characteristics of geosynthetic – soil interfaces determined by the inclined plane apparatus*, M.S. Thesis. Gdańsk University of Technology, Faculty of Civil and Environmental Engineering, Gdańsk 2008.
[6] WASTI Y., BAHADIR ÖZDÜZGÜN Z., *Geomembrane – geotextile interface shear properties as determined by inclined board and direct shear box tests*, Geotextiles and Geomembranes, 19 (2001), 45–47.