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ANALYSIS OF THE SHEAR STRENGTH OF A SOIL-GEOSYNTHETIC INTERFACE

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Abstract

The paper presents the results of the shear strength measurements of a soil-geosynthetic interface. The tests were executed using a large-size direct shear test apparatus. A total of 5 different samples of materials were tested, i.e., ash, sand, well-graded gravel, fine poorly-graded gravel, and medium poorly-graded gravel. These materials were reinforced using different types of geosynthetics, i.e., Thrace WG80 black woven geotextile, Tencate Miragrid GX55/30 woven geogrid, and Thrace TG3030S rigid polypropylene geogrid. An interface coefficient α, which represents the ratio of the soil-geosynthetic interface shear strength to the shear strength of unreinforced material sample, was determined for given combination of the material and geosynthetics. The coefficient α reached a greater value in the critical stress state than in the peak stress state for sands and gravels reinforced using GX55/30 and TG3030S geogrids. The value of the coefficient α was in a range of 0.87 - 1.04 for gravels and 1.03 - 1.19 for sand. The black woven geotextile was used as the reinforcement only in samples of sand and ash. The results pointed to the different behaviour of these materials in the testing of the interface shear strength.

Keywords:

Geosynthetics;
Geogrid;
Soil reinforcement;
Shear strength of soil;
Soil-geosynthetics interface.

1 Introduction

Soil reinforcement using geosynthetics is an often-used method of soil stabilization, which can be applied in geotechnical constructions, such as, e.g., retaining structures or walls, road and railway embankments, see e.g., [1-4]. Geosynthetics can also be applied to improve the resistance and settlement of subsoil below shallow foundations, e.g., [5]. The stability and effectiveness of these structures are significantly influenced by the interaction of the geosynthetic reinforcement and the soil and material, respectively. The interaction of the soil, different types of coarse-grained materials, and geosynthetics were investigated by many researchers, e.g., [6-8]. Technical regulation TP 97:2008 (Geosynthetics in the earth body of overland roads) states that in the design of reinforced earth structures, where the geosynthetics perform a reinforcing function, it is necessary to determine the properties of the soil-geosynthetics interaction [9]. Determining these properties is required due to the possibility of assessing the overall stability of the earth's body as well as ensuring that the shear resistance will be able to transfer the required tensile force [9]. The shear strength properties of soils and different types of materials can be determined using field/in-situ tests, see e.g., [10-11], and laboratory tests, see e.g., [12-14]. A modified large-size direct shear test apparatus can be used to determine the interface shear strength of the soil (material) on the contact with geosynthetic reinforcement, see e.g., [7, 16-18]. These tests allow for determining the soil-geosynthetic interface shear strength and an interaction coefficient α. This coefficient represents the ratio of the shear strength of the soil-geosynthetic interface to the shear strength of the unreinforced soil (material), see e.g., [19]. Empirical values of the coefficient α are also given by technical regulation TP97 [9]. In the case of coarse-grained materials, the coefficient α is recommended in the range of 0.7 - 0.9 for geotextiles and the range of 0.9 - 1.0 for geogrids. These values of the parameter α are also often used in the design of reinforced earth structures using analytical calculations or numerical modelling;

see e.g. [20-21]. The actual value of the parameter α depends on the properties of the reinforced material and the parameters of the geosynthetic reinforcement. Some researchers, e.g. [7, 16-17], state that the value of the parameter α is usually lower than 1.0; however, under certain circumstances, it may exceed the value of 1.0. In other cases, by using suitable material and geosynthetic reinforcement, laboratory tests have shown that the value of the α parameter can reach much higher values than 1.0, e.g., [18]. In general, it can be stated that values higher than 1.0 can be achieved with geogrids, where, with appropriately wedged grains in the opening area of the reinforcement, the transverse ribs can create relatively great resistance to displacement [22]. In the case of geotextiles and geomembranes, the shear strength of the soil-geosynthetics interface is given only by the friction of the soil (material) against the surface of the geosynthetic reinforcement. This causes a parameter α usually to be less than 1.0, e.g. [23-24]. The results of laboratory measurements aimed at determining the shear strength of the soil-geosynthetic interface and the parameter α for various types of geosynthetic reinforcements and coarse-grained materials are presented in this paper.

2 Testing procedure and methodology

The laboratory tests were executed on five coarse-grained cohesionless materials:

- Sample 1: Ash;
- Sample 2: Poorly-graded sand;
- Sample 3: Well-graded gravel;
- Sample 4: Poorly-graded gravel - fine;
- Sample 5: Poorly-graded gravel - medium.

The grain-size curves of the materials tested are shown in Fig. 1. The classification of the materials tested was done according to STN 72 1001: Classification of soils and rocks (2010) standard. The materials were classified as follows:

- Samples 1 and 2 - poorly-graded sand (SP);
- Sample 3 - well-graded gravel (GW);
- Samples 4 and 5 - poorly-graded gravel (GP).

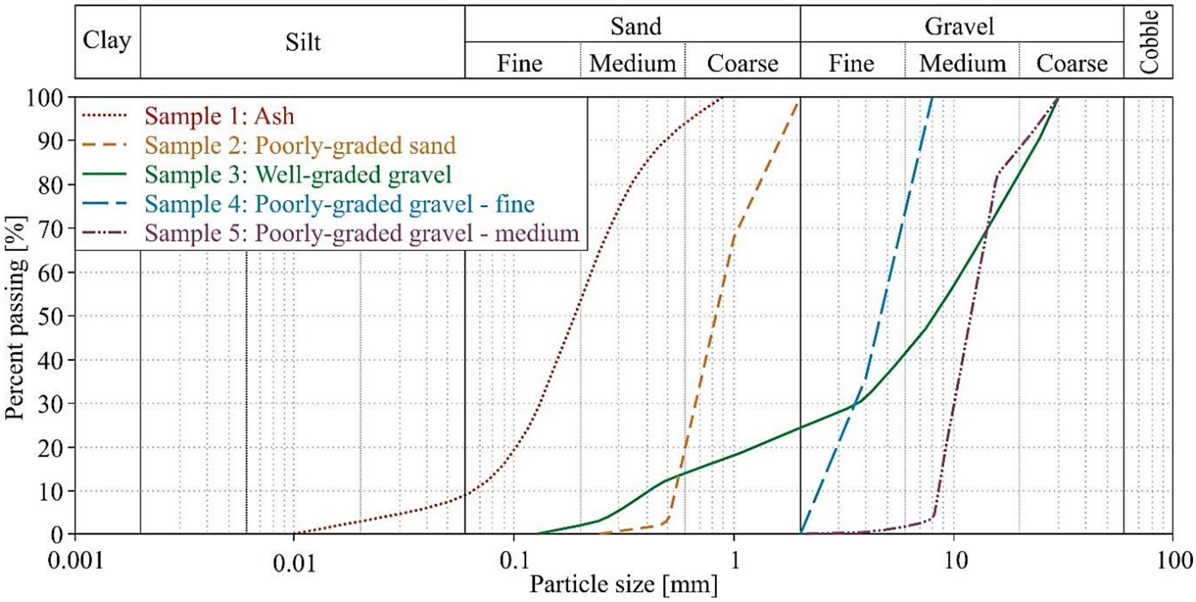

Fig. 1: Grain-size distribution curves of the materials tested.

The tests were executed with three different types of geosynthetic reinforcements, i.e., Tencate Miragrid GX55/30 (marked as GX55/30), Thrace TG3030S (marked as TG3030S), and Thrace WG80 (marked as WG80). The GX55/30 reinforcement is a "soft" woven geogrid that is made of polyester with polymeric surface protection. This type of geogrid can be used for reinforcing steep slopes, retaining walls and structures, and subsoil beneath shallow foundations. The dimensions and properties of the geogrid are given by [25]. The TG3030S reinforcement is a "stiff" polypropylene extruded biaxial geogrid. This type of geogrid is suitable for reinforcing steep slopes, retaining walls and structures, as well as reinforcing the weak and contaminated subsoil under shallow foundations or embankments. The dimensions and properties of this geogrid are given by [26]. The WG80 reinforcement is a black woven geotextile, which can be used to offer filtration, reinforcement, and separation functions. This geosynthetics is UV stabilized and produced from 100 % of polypropylene tapes. The properties of the geosynthetics are given by [27]. The photos of the geosynthetics tested are shown in Fig. 2.

Fig. 2: Geosynthetic reinforcements used in the laboratory testing.

Photo documentation from the tests is shown in Fig. 3. The laboratory tests were done using a large-size direct shear test apparatus. A shear box had a square dimension of 300 x 300 mm and a total height of 200 mm. These dimensions were also in agreement with the requirements of TP97. The tests were executed only with dried materials and focused on determining the effective (drained) shear strength properties. The speed of a horizontal movement was set in the range of 0.2 - 1.0 mm/min, depending on the material tested. The maximum horizontal movement reached about 60 mm at the end of the test. The shear tests were done for normal (vertical) stresses of about 50, 100, and 150 kPa. The basic boundary conditions for the tests conducted are stated in Table 1. The automatic recording included the exact value of the normal stress, the shear force (converted to the shear stress), and the horizontal and vertical displacement (deformation).

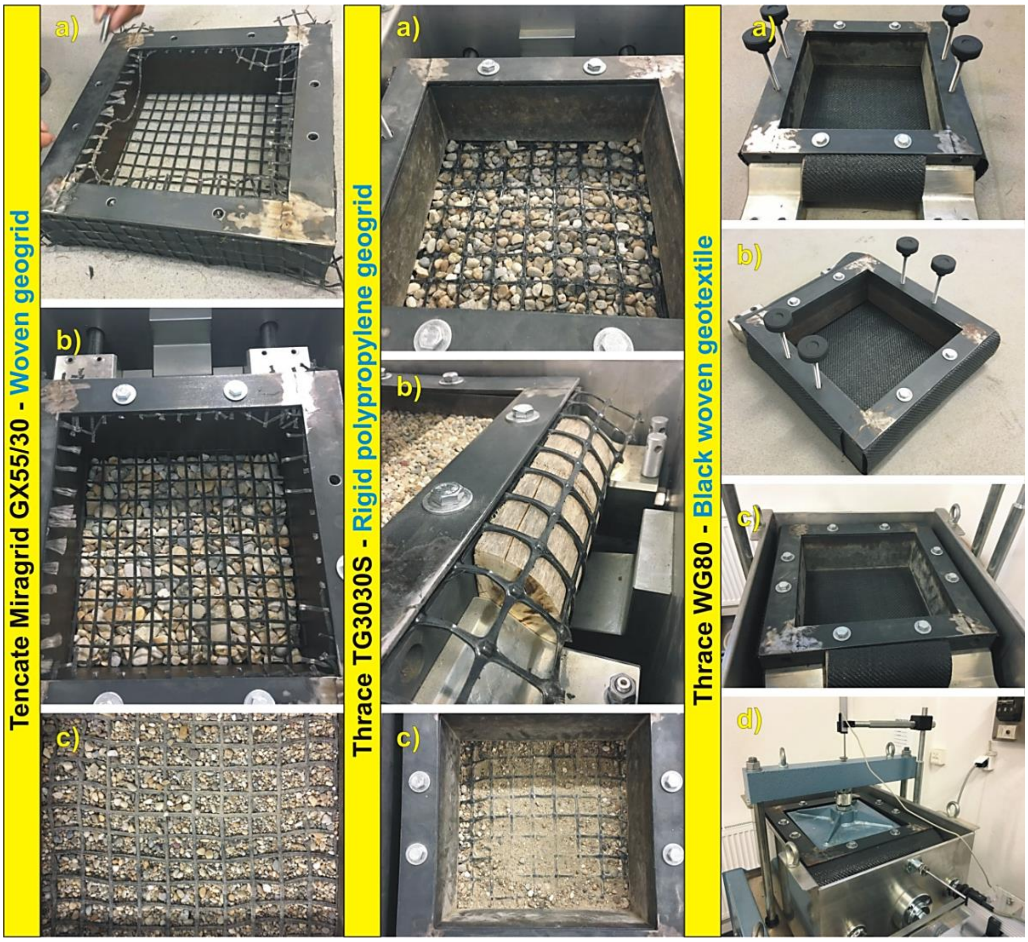

Fig. 3: Photo documentation from the laboratory testing.

The tests were done in two basic phases, i.e., the consolidation phase and the shear test phase. In the case of gravel samples, the consolidation phase was considered for about 30 minutes because only a quick deformation without any further time-dependent deformation (consolidation) occurred. A short-term consolidation was recorded in the cases of ash and sand samples. The consolidation time was only about 4 hours. A shear strength test apparatus with controlled deformation/movement was used. This allowed for determining the peak and critical shear strength properties. A more detailed description of the testing procedure has been published by the authors for unreinforced soil samples [12]. In the case of the shear tests of the soil-geosynthetics interface, the difference was that in the first step, the material tested was compacted only up to the upper edge of the lower part of the shear box, a geosynthetic reinforcement was fixed to the upper part of the shear box, and then the upper part of the shear box was placed on the lower part of the box. The geosynthetic reinforcement was placed in the shear area, which allowed for measuring the soil-geosynthetics interface shear strength. Subsequently, the rest of the material tested was added and compacted into the upper part of the shear box.

Table 1: The basic boundary conditions for the tests conducted.

Sample	**Consolidation phase**	**Shear test phase**		
	Compression/Consolidation time [min]	**Speed of the horizontal movement [mm/min]**	**Time of the shear test [min]**	**Maximum horizontal movement [mm]**
Sample 1	240	0.2	300	60
Sample 2	240	0.2	300	60
Sample 3	30	0.5	120	60
Sample 4	30	1.0	60	60
Sample 5	30	1.0	60	60

3 Results and evaluation of the laboratory measurements

In the first step of evaluating the results, diagrams of the shear strength curves and the course of the sample's vertical deformation were plotted. The diagrams of the shear strength are shown in Fig. 4 - left for Sample 1 (Ash), Fig. 5 - left for Sample 2 (poorly-graded sand), Fig. 6 - left for Sample 3 (well-graded gravel), Fig. 7 - left for Sample 4 (poorly-graded gravel - fine), and Fig. 8 - left for Sample 5 (poorly-graded gravel - medium). The results include the shear strength curves of the unreinforced sample (black) as well as the shear strength curves of the soil in contact with the geosynthetics, i.e., GX55/30 (red), TG3030S (green), and WG80 (blue). The peak and critical shear strength were determined using the methodology, which has been presented for unreinforced soils by the authors [12]. The failure lines of unreinforced materials as well as the materials reinforced using geosynthetics, for the peak and critical stress state, are plotted in Fig. 4 - right for Sample 1, Fig. 5 - right for Sample 2, Fig. 6 - right for Sample 3, Fig. 7 - right for Sample 4, and Fig. 8 - right for Sample 5.

The results allowed for determining the shear strength parameters, i.e., φ' - the peak angle of the shear strength, τ'_0 - the peak initial shear strength, φ'_c - the critical angle of the shear strength, and $\tau'_{0,c}$ - the critical initial shear strength. Naming "the initial shear strength" was used instead of "the cohesion", which is more suitable for a given type of material, see e.g., [12].

Sample 1 (Ash) was reinforced only using WG80 geosynthetics, which was suitable for a given type of material. The material has contracting behaviour in all the tests. The results in Fig. 4 showed that almost no difference occurs between the shear strength curves of the unreinforced material and the interface shear strength. Sample 2 (poorly-graded sand) was tested with all three geosynthetic reinforcements, Fig. 5. The sample had a significant dilative behaviour. In the cases of GX55/30 and TG3030S geogrids, the results showed that the peak shear strength of the unreinforced material and the soil-geosynthetic interface are similar to each other. The soil-geosynthetic interface shear strength is significantly greater than the shear strength of the unreinforced soil in the critical stress state.

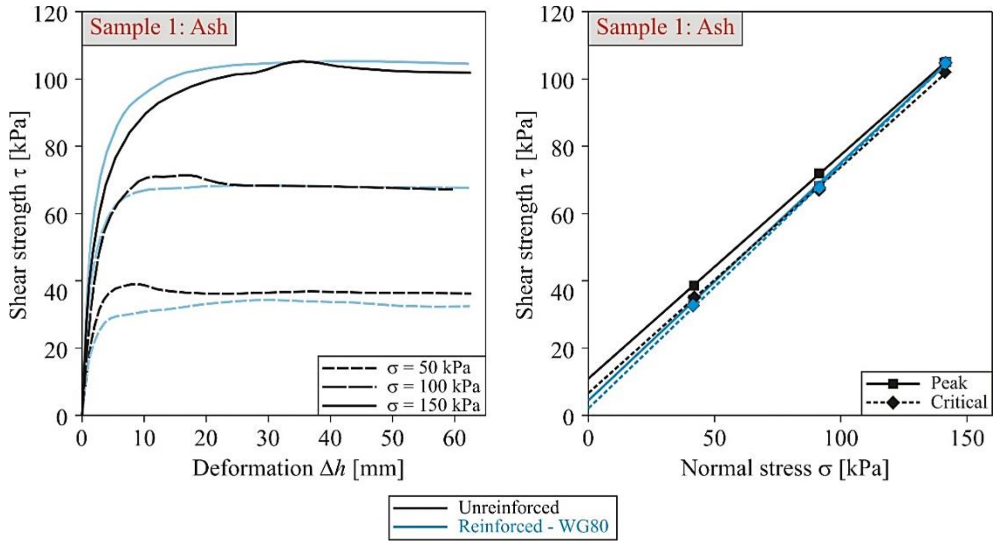

Fig. 4: Diagrams of the shear strength (left) and the failure envelope lines - Sample 1.

A significantly different behaviour occurred in the case of the material reinforced using WG80 geosynthetics. The interface shear strength in the peak stress state showed significant initial shear strength and reduction of the angle of the shear strength. In the critical stress state, almost no difference occurred between the shear strength of the unreinforced material and the shear strength of the soil-geosynthetics reinforcement. In the case of Sample 3 (well-graded gravel), see Fig. 6, the interface shear strength was lower than the shear strength of the unreinforced material in the peak and the critical stress state. This effect was caused mainly by the technique of installation of the geosynthetics into the shear box and the compaction of the sample - described in the discussion. In the case of Sample 4 (poorly-graded gravel - fine), see Fig. 7, the soil-geosynthetics interface shear strength (for both geosynthetics tested) was a little lower than the shear strength of the unreinforced sample in the peak stress state and a little greater in the critical stress state. The results of Sample 5 (poorly-graded gravel - medium), see Fig. 8, showed that the soil-geosynthetic interface shear strength is almost the same then the shear strength of the unreinforced material when the TG3030S geogrid is used. If the GX55/30 geogrid is used, the interface shear strength is a little lower than the shear strength of the unreinforced sample. This can be seen in the peak as well as critical stress state.

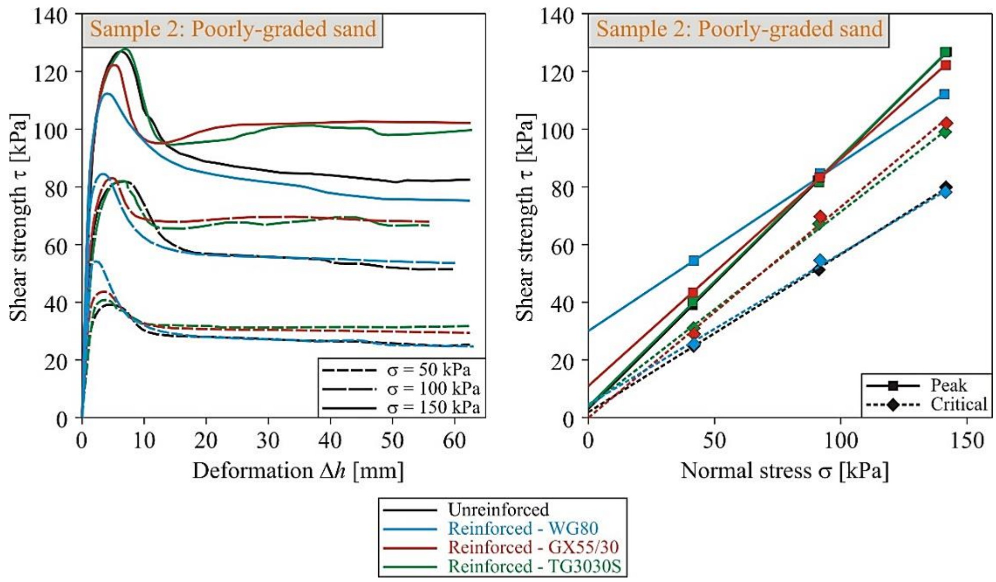

Fig. 5: Diagrams of the shear strength (left) and the failure envelope lines - Sample 2.

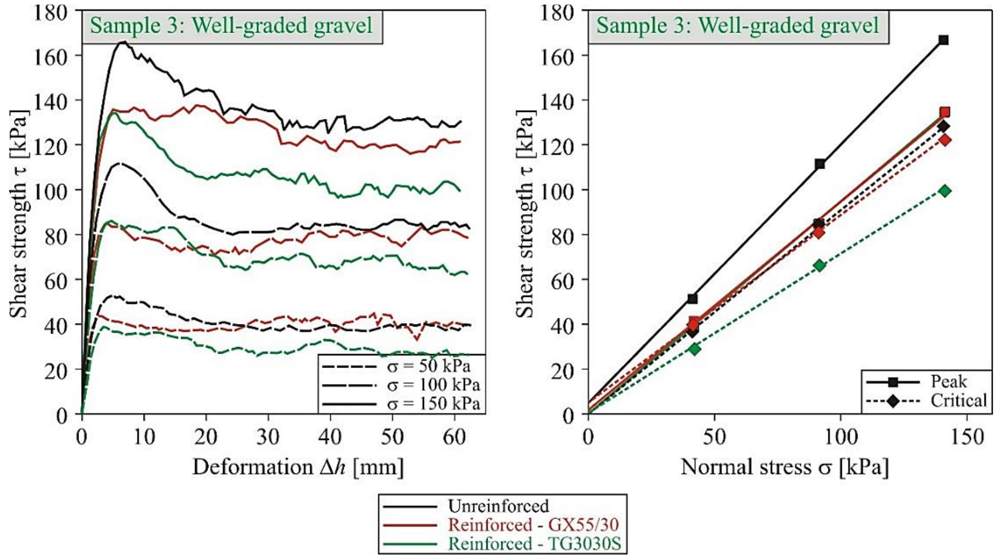

Fig. 6: Diagrams of the shear strength (left) and the failure envelope lines - Sample 3.

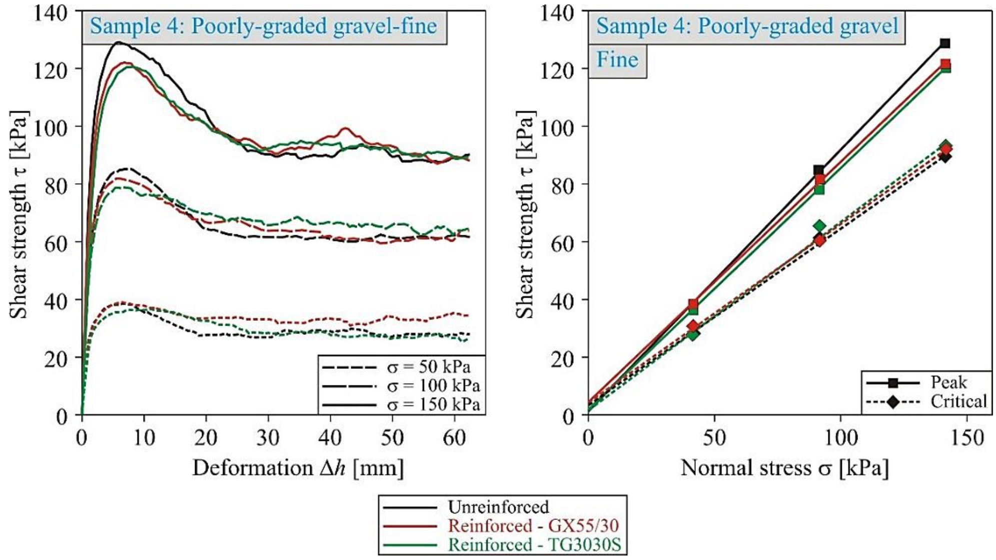

Fig. 7: Diagrams of the shear strength (left) and the failure envelope lines - Sample 4.

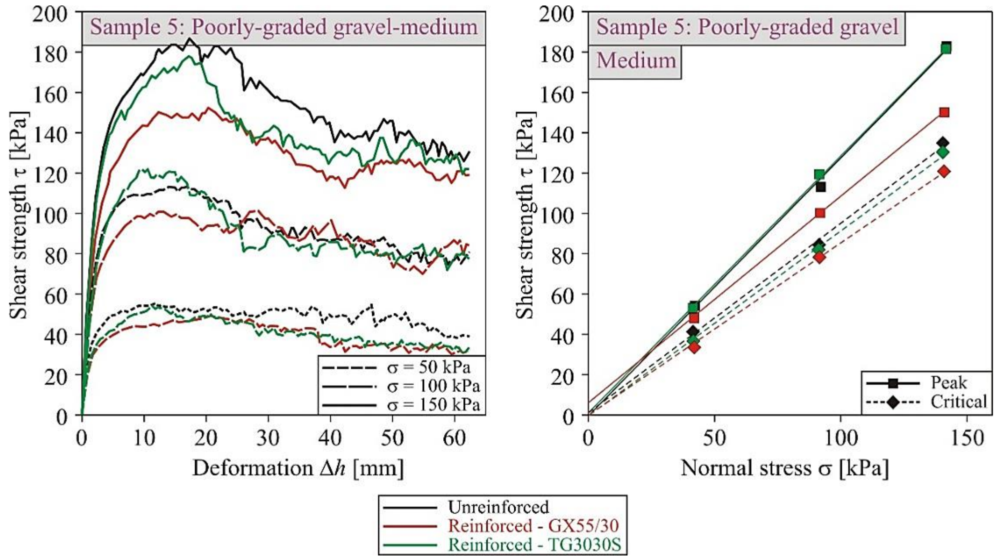

Fig. 8: Diagrams of the shear strength (left) and the failure envelope lines - Sample 5.

Based on the result of the measurements the interface coefficient α was determined. The basic formula for determining this coefficient can be stated as follows:

$$\alpha = \tau_{soil\text{-}geosynthetics} / \tau_{soil} , \quad (1)$$

where $\tau_{soil\text{-}geosynthetic}$ is the peak or critical interface shear strength and τ_{soil} is the shear strength of the unreinforced material. The values of the interface coefficient α are stated for given combinations of the materials tested and the geosynthetic reinforcements in Table 2. The values are stated for the peak stress state τ_p and critical stress state τ_c. In most cases, the coefficient α reached a greater value for the critical shear strength than for the peak shear strength. If the WG80 geosynthetics was used, the interface coefficient α oscillates about the value of 1.0. In the cases of "soft" and "stiff" geogrids, the interface coefficient α depends on the grain size of the material tested. What is important here is how the grains of individual sizes wedge together in the open area of the geogrid.

Table 2: Values of α coefficient determined by laboratory testing.

Sample	Shear strength	Reduction coefficient α(-)		
		Reinforcement		
		WG80	GX55/30	TG3030S
Sample 1 Coarse ash	τ_p	0.96	-	-
	τ_c	1.00	-	-
Sample 2 Sand poorly-graded	τ_p	1.03	1.03	1.01
	τ_c	1.03	1.19	1.19
Sample 3 Gravel well-graded	τ_p	-	0.80	0.77
	τ_c	-	0.99	0.78
Sample 4 Gravel poorly-graded - fine	τ_p	-	0.97	0.94
	τ_c	-	1.04	1.03
Sample 5 Gravel poorly-graded - medium	τ_p	-	0.87	1.00
	τ_c	-	0.88	0.94

In the peak shear strength, the effective dilatancy angle (ψ') is an important parameter. This parameter can be determined in the case of coarse-grained material with dilative behaviour using the following formula:

$$\tan(\psi') = \Delta v / \Delta u, \quad (2)$$

where Δv is an increment of vertical deformation and Δu is an increment of shear displacement, see e.g., [28]. The dilatancy angle depends on the normal stress applied - decreases with increasing normal stress. Because of this, the following dilatancy angles were determined for the samples tested: ψ'_{50} - for the normal stress of 50 kPa; ψ'_{100} - for the normal stress of 100 kPa; ψ'_{150} - for the normal stress of 150 kPa; ψ'_{mean} - as the mean value; and $\psi'_{average}$ - as the average value. All the values of dilatancy angles for Samples 2 - 5 are stated in Table 3. The results showed that the dilatancy angle determined can significantly differ in the case of the unreinforced material sample and the soil-geosynthetics interface. However, the analysis of the results showed that it is not possible to establish specific dependencies between individual measurements, mainly between the unreinforced samples and the soil-geosynthetics interfaces.

Table 3: Values of the dilatancy angle determined by laboratory testing.

Sample		**The angle of the dilatancy**				
		Ψ_{50}°	Ψ_{100}°	Ψ_{150}°	Ψ_{mean}°	$\Psi_{average}$°
Unreinforced						
Sample 2	Poorly-graded sand	14.20	13.37	12.50	13.37	13.36
Sample 3	Well-graded gravel	18.71	17.81	15.97	17.81	17.50
Sample 4	Poorly-graded gravel-fine	15.64	14.54	14.17	14.54	14.78
Sample 5	Poorly-graded gravel-medium	21.39	19.89	18.78	19.89	20.02
Reinforced - WG80						
Sample 2	Poorly-graded sand	9.71	8.72	8.15	8.72	8.86
Reinforced - GX55/30						
Sample 2	Poorly-graded sand	16.37	13.84	13.46	13.84	14.56
Sample 3	Well-graded gravel	16.67	12.01	11.40	12.01	13.36
Sample 4	Poorly-graded gravel-fine	15.41	14.97	13.84	14.97	14.74
Sample 5	Poorly-graded gravel-medium	17.94	16.52	15.65	16.52	16.70
Reinforced - TG3030S						
Sample 2	Poorly-graded sand	15.03	12.77	11.46	12.77	13.09
Sample 3	Well-graded gravel	15.44	14.67	14.01	14.67	14.71
Sample 4	Poorly-graded gravel-fine	15.43	14.42	13.05	14.42	14.30
Sample 5	Poorly-graded gravel-medium	21.70	19.91	17.35	19.91	19.65

4 Discussions

In the case of geogrid, an increase or decrease in the soil-geosynthetics interface shear strength depends on the internal shear strength of the material within the geogrid's open area, the friction between the material and the surface of the geosynthetics, and mobilization of the resistance between the material and the transverse ribs; see e.g., [21]. The shear strength of the material within the geogrid's open area usually has no impact on the change of the interface coefficient α, and the interface's shear strength is equal to the shear strength of the unreinforced material, Fig. 9. The friction between the material and the surface of the geogrid (mostly between the material and the longitudinal ribs) usually causes a reduction of the interface coefficient α, Fig. 10. This reduction depends on the geometry and material of the geosynthetics, as well as the size and shape of grains of the material tested. The mobilization of the resistance between the material and the transverse ribs can cause increases in the interface coefficient α, Fig. 11. This depends mainly on the thickness of the geogrid used and the size and shape of grains of the material tested.

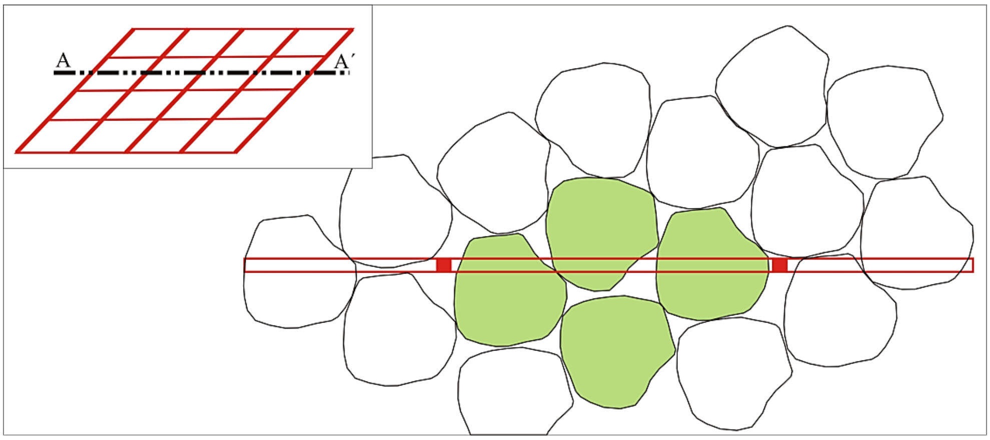

Fig. 9: Cross-section scheme: the internal shear strength of the material within the geogrid's open area.

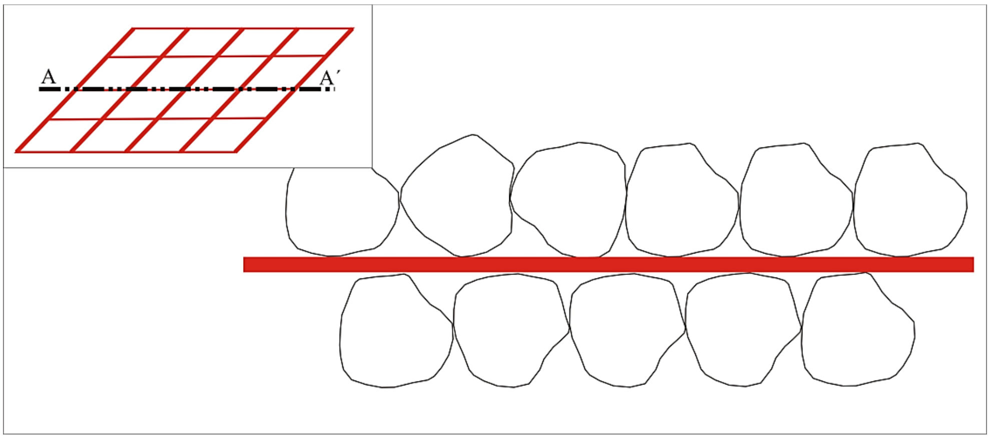

Fig. 10: Cross-section scheme: the shear strength between the material and the surface of the geosynthetic reinforcement.

Especially in the case of poorly-graded gravels with relatively large porosity, the passive resistance to displacement is not mobilized on all transverse ribs equally - this is also illustrated in Fig. 11. The smaller grains allow for better mobilization of the resistance of the transverse ribs. This effect causes the interface coefficient α to be the largest in the case of Sample 2; and decreases gradually for Samples 4 and 5 depending on their grain size. In the case of Sample 3 (well-graded gravel), the interface shear strength was lower than the shear strength of the unreinforced soil sample, especially in the peak stress state. This effect was caused mainly by the compaction technique and installation of the geogrid tested. Before placing the geogrid into the shear area, the sample was compacted in the lower part of the shear box. Small sand grains filled pores between larger gravel grains, and a relatively "smooth surface" of the sample was formed at the location of the shear surface. Subsequent fixing the geogrid and placing the sample into the upper part of the box did not cause sufficient wedging of the grains - this led to determining relatively small values of the interface shear strength α. The following measurements showed that significantly higher values of the α coefficients cans be achieved when a relatively thin layer of the sample below the shear area stays uncompacted before placing the geogrid. This part of the material is then compacted together with the material in the upper part of the shear box. The soil grains are interlocked in a better way, and the resistance of the traverse ribs is better mobilised. This technique allows determining the interface coefficient α of about 0.9 for GX55/30 geogrid and 0.95 for TG3030S geogrid. A significantly different behaviour was determined in the case of the materials reinforced using WG80 geosynthetics. In the case of Sample 2 (poorly-graded sand), the interface shear strength was affected by a wedging of sharp-edged sandy grains into the intertwined surface structure of the WG80 geosynthetics, see Fig. 12. This effect was measured as "cohesion" in the interface shear strength in the peak stress state. In the case of Sample 1 (Ash), this effect was not measured because the ash´s grains had round grains - due to this reason, no significant difference was determined between the shear strength of the unreinforced material and the interface shear strength.

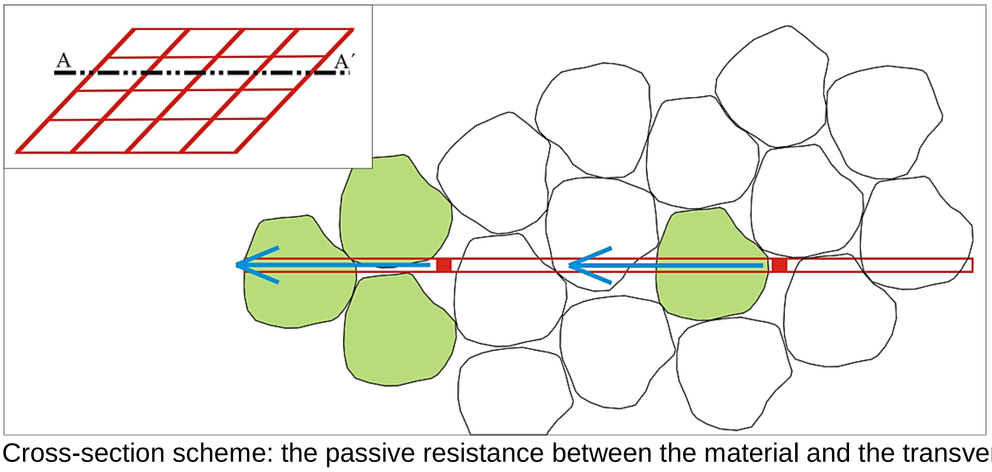

Fig. 11: Cross-section scheme: the passive resistance between the material and the transverse ribs.

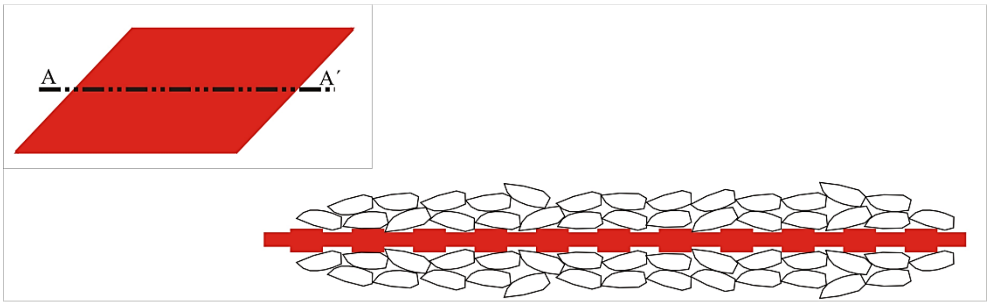

Fig. 12: Cross-section scheme: the friction between the sharp-edged material and the surface structure of the geosynthetic material.

5 Conclusions

The shear strength properties of the soil-geosynthetics interface are one of the main properties required in the geotechnical design of the reinforced earth structure. An interface coefficient α is introduced, which represents the ratio of the soil-geosynthetics interface shear strength to the shear strength of the unreinforced material. This interface coefficient, named in different ways, is also essential in designing reinforced geotechnical structures using analytical calculations or numerical modelling. The results of the measurements of the soil-geosynthetic interface shear strength are presented. The tests were executed using a large-size direct shear test apparatus. A total of 5 different materials were tested, i.e., Sample 1 - Ash; Sample 2 - Poorly-graded sand; Sample 3 - Well-graded gravel; Sample 4 - Poorly-graded gravel - fine; and Sample 5 - Poorly-graded gravel - medium. The tests were executed using three different geosynthetic reinforcements, i.e., Thrace WG80 black woven geotextile, Tencate Miragrid GX55/30 woven geogrid, and Thrace TG3030S rigid polypropylene geogrid. Sample 1 was tested with WG80 geosynthetics, while Samples 3 - 5 were tested with GX55/30 and TG3030S geosynthetics. Sample 2 was tested with all three geosynthetics. These combinations were assumed as the most relevant. The results of the measurements can be summarized in the following points:

- The interface coefficient α can usually be achieved greater in the critical shear strength than in the peak shear strength.
- In the case of poorly-graded gravels reinforced by geogrids with relatively high porosity, the coefficient α values are lower or equal to 1.0; because the passive resistance of the transverse ribs cannot be fully mobilised.
- In the case of the sand sample, the resistance of the transverse ribs can be fully mobilised, which causes the interface coefficient α to be greater than 1.0.
- It can be stated in general that the interface coefficient α increases with decreasing the grain sizes of the poorly-graded materials tested.
- A compaction technique and the way the geosynthetics are placed have a greater influence on the soil-geosynthetics interface shear strength in the case of well-graded coarse-grained materials than in the case of poorly-graded materials.
- Improper compaction techniques and processes of the geosynthetics placing can lead to determining relatively low values of the interface coefficient α for the well-graded materials.
- In the case of black woven geosynthetics, the material and surface of the geosynthetics, as well as the size and shape of the material grains have a decisive influence on the soil-geosynthetics interface shear strength.

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