INVESTIGATION OF INTERACTION BEHAVIOUR OF CEMENT-STABILIZED COHESIVE SOIL AND PVA GEOGRIDS

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ABSTRACT: Soil improvement by addition of cementation material or by incorporation of geosynthetic reinforcement is being successfully applied for cohesive soils. In many cases both stabilisation techniques can be combined to join their advantages for constructions in or from poor local cohesive soils saving costs and natural resources. The evaluation of the literature available shows that there is tremendous information about soil stabilisation with cement or geosynthetic reinforcement, but only very limited information about their combination. For the aforementioned reason, a comprehensive laboratory testing programme was carried out in order to study the effect of inclusion of cement and PVA-geogrid-reinforcement on the physical and engineering behaviour of soft clay. Series of unconfined compression, Proctor, shear and friction tests were conducted with a cement content varying from 3% to 9% with a curing period of 7 days. The main focus of this study is the interface shear-strength behaviour in the geogrid contact area which knowledge is essential for stability analysis of geosynthetic structures. In the study a recently developed novel testing device with negligible influence of device configuration constraints on test results is used. First results are presented showing interesting mechanical properties for 6% cement content in a typical cohesive soil with and without geogrid reinforcement. The cement stabilisation with embedded PVA-geogrid significantly improves the shear strength of clay soil. For the geogrid tested high coefficients of interaction in the important shear mode were registered.

1 INTRODUCTION

Throughout the world there is an increasing demand for geotechnical structures which are not only economical, but also more acceptable from the ecological point of view. There is a global tendency to use poor local mainly cohesive soils as construction material or as sub-base to reduce the costs and to save natural resources. If the properties of the local available soil do not fulfil the geotechnical and/or technological requirements, very often these cohesive soils are being modified using lime or cement stabilization on site.

In many cases soils have to be additionally reinforced by using geosynthetics, e. g. in embankments, steep slopes etc. These reinforcing techniques begin to be used also for cement-stabilized cohesive soils. PVA-geogrid-reinforcement seems to be an efficient solution due to high tensile moduli and low creep combined with high alkaline resistance (Alexiew et al., 2000). The latter is the case for cement-stabilized soils having typically a pH >12.

A safe and economic design of soil reinforcement with geosynthetics in such a new application requires a better understanding of the fundamental mechanisms of the interaction between soil and reinforcement.

In the presented study a recently developed novel testing device with negligible influence of device configuration constraints on test results is used.

The main purpose of this study is to investigate the interface strength behaviour of cement stabilized cohesive soils with embedded PVA-geogrid-reinforcement. The gained results will provide an important contribution to the efficient use of geosynthetics in innovative civil engineering applications. For these intentions broad soil mechanical tests on soil-cement-mixture and moreover extensive shear- and pullout tests on soil-cement-geosynthetic-compound-systems were planned. In this paper first results are represented and discussed.

2 CEMENT STABILISATION & GEOGRID REINFORCEMENT

Most civil engineering operations are carried out in soil and, obviously, poor soil conditions have to be encountered on the construction site. If such soil cannot be removed, its engineering behaviour can often be enhanced by some method of ground treatment. Treatment methods aim at preventing ingress of groundwater or removing it from the site on the one hand or improving soil strength on the other hand. The type of technique chosen depends on the nature of the problem and the type of soil conditions. Costs and protection of nature are obviously factors that enter into the equation. Soil is one of the most abundant and cheapest construction materials. So its use can be greatly extended by enhancing its engineering performance, for example by the addition of cementation material or by incorporation of geosynthetic reinforcing elements.

The objectives of mixing additives, commonly cement or lime with soil, are to improve volume stability, strength and stress-strain properties, permeability, and durability. The development of high strength and stiffness is achieved by reduction of void space, by bonding particles and aggregates together, by maintenance of flocculent structures, and by preventing of swelling. The permeability is altered by modification of pore size and distribution.

Like other construction materials with limited strength, soil also can be reinforced with foreign material to form a composite material that has increased shear strength and some apparent tensile strength. When geosynthetics are included in soil they improve its engineering performance and also lower the cost of construction (Giroud, 1986). The concept of soil reinforcement with geosynthetics is a technique where tensile elements are placed in the soil to improve stability and control deformation.

In many cases both above mentioned stabilisation techniques can be combined to join their advantages and fulfil the requirements for constructions in poor local mainly cohesive soils under lower costs and by saving natural resources. The examination of the relevant literature showed that there is tremendous information about soil stabilisation with cement or soil reinforcement with geosynthetics, but very limited information about their use in combination.

3 MATERIALS TESTED

3.1 *Soil*

The soil sample used in the present study was obtained from the region of Chemnitz, Germany. It is one of the most common local typical poor cohesive soil. The soil is classified as inorganic clay of high plasticity. It has a maximum dry specific density of 1.695 kN/m^3 and an optimum moisture content of 18.3 %. Some engineering properties of the clay are summarized in Table 1.

Table 1 Properties of the cohesive soil used

Property	Unit	
Initial water content w	[%]	24.10
Specific density ρ_s	[g/cm^3]	2.757
Liquid limit w_L	[%]	53
Plastic limit w_P	[%]	24
Plasticity $I_P = w_L - w_P$	[%]	29
Cohesion c'	[kN/m^2]	46
Angle of internal friction φ'	[°]	29.70
Organic content	[%]	3.2

3.2 *Stabilizer*

Generally any type of cement may be used for soil stabilization but common Portland cement is most widely used. The two principle factors that determine the suitability of a soil-cement combination with common Portland cement are, firstly, whether the soil and cement can be mixed satisfactorily and, secondly, whether the soil-cement-mixture will harden adequately (Bell, 1993). Selecting a stabilizer, the type of soil to be stabilized, the purpose for which the stabilized soil will be used, the type of soil quality improvement desired, the required strength and durability of stabilized soil, the costs and environmental conditions have to be considered. In this study as best suited additive for stabilization Portland-limestone Cement "CEM II/A-LL 32.5 R (EN 197-1)" with rapid early strength was chosen.

3.3 *Geogrid*

The reinforcement used in this study was a FORTRAC® geogrid R 750/50-30 M of PVA yarns. This type of geogrid seems to be an efficient solution due to high tensile moduli and very low creep tendency combined with high alkaline resistance(Alexiew et al., 2000). The latter is the case for cement-stabilized soils which have a pH >12. A summary of some properties of this geogrid is presented in Table 2.

Table 2 Geogrid parameters

Property	Unit	
Type	flexible, 30 mm mesh size	
Ultimate Tensile Strength (UTS)	[kN/m]	≥ 750
Ultimate Strain	[%]	≤ 6
Tensile force at 2% strain	[kN/m]	≥ 230
Tensile force at 3% strain	[kN/m]	≥ 330
Chemical and biological durability	[-]	very high

4 ENGINEERING PROPERTIES OF SOIL-CEMENT MIXTURE

It is known that the addition of small amounts of cement, up to 2%, modifies the properties of a soil, while large quantities cause radical changes in these properties. In fact cement contents may range from 5 to 15% by dry weight of soil, depending on the type of soil and properties required. The reaction of cement in soil, particularly in cohesive soils, is very complex and differs from the cement hydration in concrete. As the grain size of granular soils is larger than that of cement, the individual grains are coated with cement paste and bonded at their point of contact. The particles in cohesive soils are much smaller than cement grains and, consequently, it is impossible to coat them with cement. In practice, cohesive soils are broken into small fragments which are coated with cement and than compacted. The hydration products formed after short periods of ageing are gelatinous and amorphous which, with time, harden due to gradual desiccation.

The purpose of laboratory testing is to determine the minimum cement content needed to harden the material adequately and to obtain the optimum moisture content (OMC) and density values to be used for construction. According to the German Technical Testing Regulation of Soil and Rock in Road Construction (FGSV, TP BF-StB. Part B 11.1, 2003) OMC and maximum density are determined by the Proctor test and the required cement content is determined by either the unconfined compressive strength test for base course located in non-frost areas and an additional freeze-thaw test for base course located in frost areas.

In this study no explicit requirements for broad properties of compacted cement-stabilized soil are made – except for the shear-strength, which is the first requisite for quality soil-cement-geosynthetic-reinforced systems.

In order to decide about the appropriate cement content and to attain proper moisture content, density and shear strength, for further interaction tests (Chap. 5), following tests are conducted under the guidelines of FGSV, TP BF-StB. Part B 11.1 (2003):

- Proctor Test - DIN 18127 (1997-11)
- Compressive Strength Test - DIN 18136 (2003-11)
- Direct Shear Test - DIN 18137-3 (2002-09)

The specimens are examined at 3 different cement contents, 3%, 6% and 9% by dry weight of soil.

4.1 *Specimen preparation*

In order to achieve a uniform material with minimum cement content, the guidelines for specimen preparation of FGSV, TP BF-StB. Part B 11.1 (2003) are to be considered, since good mixing of stabilizers with soil is the most important factor affecting the final quality. For example a long period of mixing brings about partial hydration of the cement with a resultant loss of strength at constant density. If compaction is delayed the cement begins to hydrate and therefore the soil-cement begins to harden. As a result the mixture becomes more difficult to compact (Ingles et al. 1972). For comparability reasons the soil-cement-mixtures are mixed 90 seconds and compacted after 60 minutes of waiting time.

4.2 *Influence of the addition of cement on the compaction of clay soil*

Standard proctor tests according to DIN 18127 (1997) were performed on the samples mentioned above to analyse the effect of the addition of cement content on the compaction of soil-cement-mixture. The results are summarised in Table 3.

Table 3 Influence of the addition of cement on the compaction of clay soil 1 hour after mixing

Cement ratio by weight [%]	Dry density [g/cm³]	Moisture content [%]
Untreated soil	1.695	18.30
3%	1.661	16.50
6%	1.678	15.00
9%	1.678	16.80

The addition of cement to clay soil reduces noticeably the optimum moisture content and marginal the maximum dry density for the same compaction effort (Table 3).

4.3 *Compressive strength of molded soil-cement cylinders*

The unconfined compressive strength value q_u at failure is determined in a way-controlled unconfined compression test according to DIN 18136 (2003). The objective of this test was to determine the appropriate amount of cement. The relationship between cement content and unconfined compressive strength of 7 days cured cylindrical samples are shown in Figure 1.

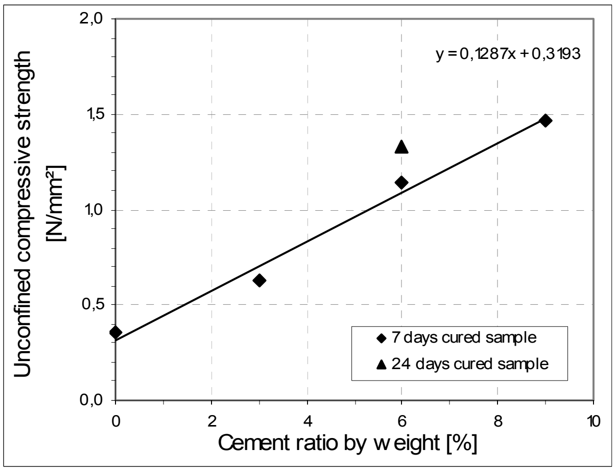

Figure 1 Relationship between cement content and unconfined compressive strength for soil-cement-mixture

The strength of soil-cement tends to increase in a linear manner with increasing cement content. In order to analyse the influence of curling time on the unconfined compressive strength with different amount of cement further tests are planned. First results for 6% cement content shows an influence of time. The value is increasing from 1.143 N/mm² (7d) to 1.335 N/mm² (28d) at otherwise same conditions (Fig. 1).

4.4 *Shear strength of cement stabilized clay soil*

Direct shear box tests according to DIN 18137-3 (2002) were performed on the samples to determine the shear strength parameters of the cement stabilized soil for different cement contents. The objective of this test was also to determine the appropriate amount of cement. For this purpose a standard apparatus with a circular cell with 94 mm diameter and 16 mm height was used. The soil-cement-mixtures were saturated. Each test was carried out – after a constant consolidation time of 6 hours – at a constant shear displacement rate of 0.01 mm/min. The shear tests were performed at normal stresses of 50 kN/m², 100 kN/m² and 200 kN/m² up to a total shear displacement of 18 mm.

The effect of cement content on shear strength can be seen and understood best by plotting and comparing peak strength envelopes and the development of cohesion and friction angle respectively. Figure 2 illustrates the Mohr-Coulomb failure envelopes for peak strengths of untreated and cement stabilized soil at different cement contents. The obtained values of peak strength parameters cohesion *c* and friction angle φ are extracted in Table 4. Figure 3 presents the corresponding peak friction angle and cohesion vs. cement ratio.

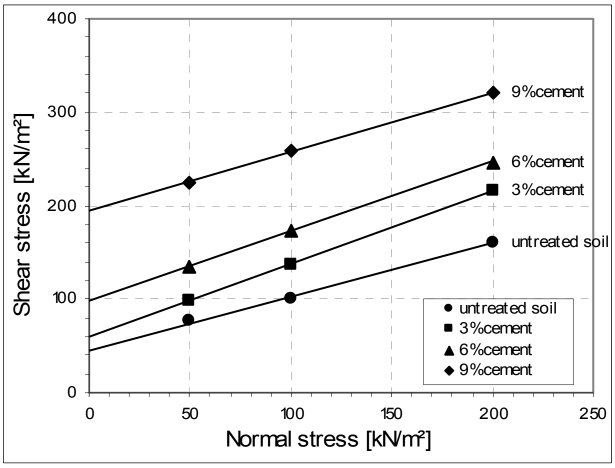

Figure 2 Peak strength envelopes of soil-cement-mixture

Table 4 Shear strength parameters

Cement ratio by weight [%]	Peak parameters Angle of internal friction φ [°]	Cohesion *c* [kN/m²]
Untreated soil	29.7	46
3%	38.5	57
6%	36.8	98
9%	32.5	193

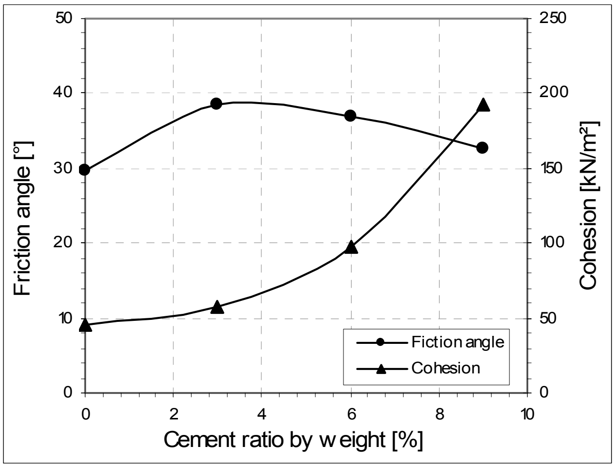

Figure 3 Peak friction angle and cohesion vs. cement ratio

It is clear that the cement stabilisation significantly improves the shear strength of clay soil. The results show that there is an increasing in both cohesion and peak friction angle value (Fig. 2). Nevertheless the cohesion tends to increase considerably non linear with increasing cement content and the peak friction angle reaches high values by small cement contents (Fig. 3).

4.5 *Determination of the appropriate cement ratio*

The tests mentioned above were performed finally with the aim to decide about the appropriate cement content and proper moisture content, density and shear strength for the further geogrid interaction tests (Chap. 5). The soil-cement-mixtures were examined at 3 different cement contents, 3%, 6% and 9% by dry weight of soil.

Under consideration of the test results as well as costs and environmental conditions for real structures the option with 6% cement was chosen for the further tests.

5 EXPERIMENTAL INVESTIGATION OF INTERACTION BEHAVIOUR

Recent developments in the technology, which is related to the manufacturing of new and enhanced high-quality geosynthetic materials, indicate the fact, that the use of the reinforcement function of geosynthetics will be increasingly applied in new geotechnical structures.

However, as with all construction materials, the advantageous application of geosynthetic reinforcement requires a better understanding of the mechanical behaviour of reinforced soil, especially in such new applications. Usually direct shear and pull-out tests are performed to investigate the friction characteristics (the interaction soil-reinforcement), which are used for stability analysis.

Regarding necessity, in this study extensive shear- and pullout tests on soil-cement-geosynthetic-compound-systems, with pre-determined cement content, were planned to study the interface strength behaviour of cement stabilized cohesive soils with embedded PVA-geogrid-reinforcement. A recently developed novel testing device with negligible influence of device configuration constraints on test results was used.

In the following Chapters the first results are presented and discussed.

5.1 *Geosynthetic-Interaction-Testing-Device (GITD)*

For the examination of the interaction behaviour in soil-geosynthetic-compound-systems a new test device, called the Geosynthetic-Interaction-Testing-Device (GITD), has been developed. This device is capable of performing both pullout and direct shear tests. A schematic diagram of the GITD is shown in cross section in Figure 4.

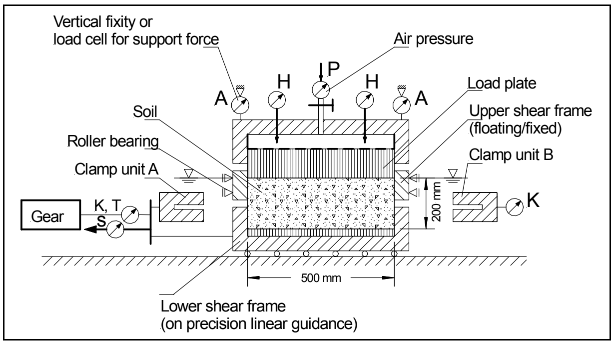

Figure 4 Cross section of the Geosynthetic-Interaction-Testing-Device (GITD) of the Geotechnical Institute of Freiberg University of Mining and Technology

Friction parameters for geosynthetic interfaces are commonly determined by using a modified direct shear test known from soil mechanics. Although this test method is longstanding and well known for testing granular materials, the modification of testing devices creates some problems in the performance of friction tests with geosynthetics. The type of testing-equipment and method of load application can affect the result of the shear test (Blümel et al. 2000).

To eliminate one of the known problems - the friction influence between the sample and the side walls of the shear frames - the GITD was constructed in such a way, that the upper shear frame can freely move during the test in vertical direction, and the size of the shear gap automatically and optimally adjusts itself according to the actual testing conditions.

In comparison with known geosynthetic testing practice, the construction of the presented new test device (GITD) offers furthermore the special advantage, that a wide range of innovative shear and pullout test procedures can be carried out in the same device and with negligible influence of test device configurations on the test results (Aydogmus et al. 2002).

The upper shear frame has a 500 mm x 500 mm shear plane area. The lower shear frame is 100 mm longer than the upper one so that, if desired, the contact area is constant during the shear test. The height of both frames together is 200 mm. Normal stress is applied by air pressure via a membrane. The rubber air bag is capable of providing uniform normal pressures up to 600 kN/m². The gear provides constant rates of displacement between 0.000001 mm/min - 12 mm/min and a maximal pull- or shear force up to 125 kN.

The GITD has been developed at the Geotechnical Institute of Freiberg University of Mining and Technology (Aydogmus et al. 2001).

5.2 *Specimen preparation*

The specimen preparation was in general equal to that described in Chapter 4.1. The only difference results from the difficulty to prepare homogenous and isotropic soil-cement-mixture in a huge amount, approximately 90 kg per test. For this reason the components of the mixture were mixed in calculated amounts with a laboratory blender until visual inspection indicated uniform distribution, in general max. 240 minutes.

After 60 minutes of delay, the material was placed into the shear device and compacted to the previous determined density (Chap. 4).

To prevent pore water pressure, the normal pressure was applied in steps. The soil-cement-mixtures were saturated. Each test was carried out – after a constant consolidation time of 14 hours – at a constant shear displacement rate of 0.2 mm/min. Both the soil and soil-geogrid shear tests were performed at normal stresses of 50 kN/m², 100 kN/m² and 200 kN/m² up to a total displacement of 85 mm. Some deviations in the soil data result from the larger sample volume.

5.3 *Results and discussion of the performed shear and friction tests*

The obtained results show very interesting mechanical properties without and with geogrid reinforcement. Note, that the following results represent the strength of the soil-cement-mixture in a relatively early age (~ 14 hrs.).

The shear stress – displacement behaviour of cement stabilized and reinforced soil is quite different from that of untreated and unreinforced soil (Fig. 5). For untreated and unreinforced cohesive soil the well known curve shows (as expected) a maximum strength at large displacements followed by a smooth decrease to a residual value. For untreated soil with the geogrid the peak value is higher and takes place at smaller displacements. The highest peak shear strength is registered for the treated soil with the geogrid at even smaller displacements. Correspondingly, a higher decrease back to a residual value takes place.

A possible interface softening due to the implemented geogrid does not occur. The data seem to confirm a synergetic effect of cement stabilization and geogrid inclusion for the materials tested in the sense of increasing both strength and stiffness in the shear mode.

Generally shear (and similarly: pull-out) tests for geosynthetic-soil combinations are a priori of phenomenological nature. Internal mechanisms and the influence of different factors as soil and geogrid parameters and structure, surface-roughness of geosynthetic, polymers used, mesh size etc. are hardly clarified and not really transparent. Thus, the authors prefer to avoid any hypothesis at present. In any case, the interaction geogrid-soil is even better than the "interaction" soil-soil itself.

With increasing hydration time higher strengths by smaller displacements are to be expected.

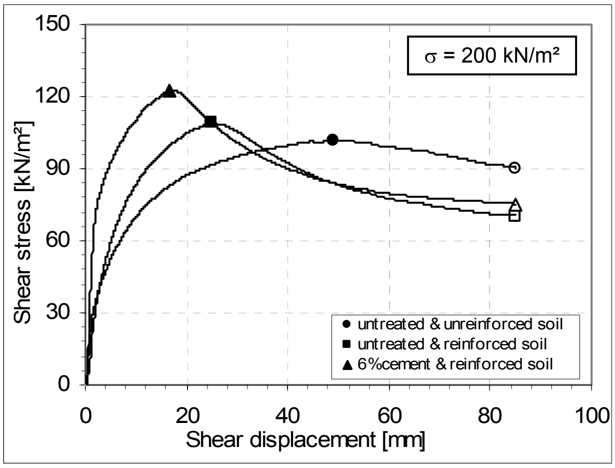

Figure 5 Shear stress vs. shear displacement (σ = 200 kN/m²)

The vertical displacement – shear displacement behaviour is also quite different for the different cases (Fig. 6). For untreated and unreinforced clay the curve shows a steady settlement with continuous shear displacement, a cemented and reinforced soil shows an after-peak-shear-way with a very small increase of settlement. An analogous positive synergetic effect as mentioned above for geogrid and cemented soil occurs, reducing the maximum settlement by 55 %. Consolidation time and settlement of cemented soil was considerably shorter respectively smaller than of untreated soils. This can be explained with the hydration of the cement, reducing plasticity increasing shear strength.

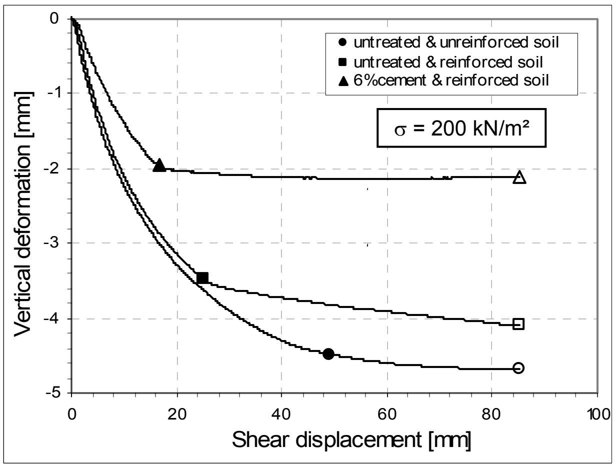

Figure 6 Vertical deformation vs. shear displacement (σ = 200 kN/m²)

Figure 7 presents the Mohr-Coulomb failure envelopes of geogrid with cement stabilized soil and geogrid with untreated soil. The cement content significantly improves the shear strength of poor cohesive soil, which is known. No negative influence of the geogrid used on that increase has been registered.

The obtained values from tests until now of peak strength parameters cohesion *c* and friction angle φ for four different cases as combinations of cemented/non-cemented soil without/with geogrid are summarized in Table 5. Both cohesion and peak friction angle are increased.

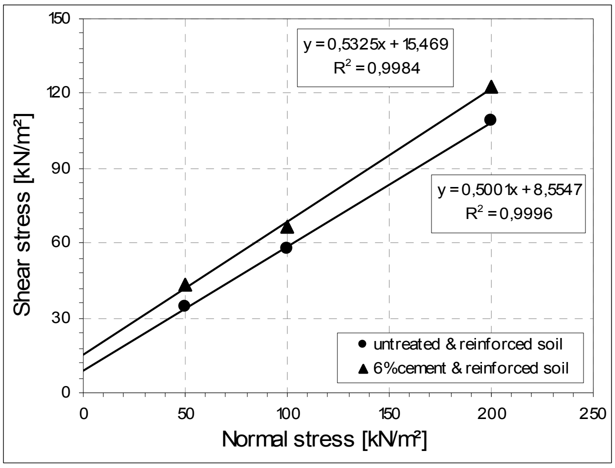

Figure 7 Peak strength envelopes for geogrid with cemented and non-cemented soil

Table 5 Shear strength parameters for typical cases tested

	Peak parameters	
	Friction angle φ [°]	Cohesion *c* [kN/m²]
non-cemented, no geogrid	~23	~17
non-cemented, with geogrid	~27	~9
cemented, no geogrid	~30	~14
cemented, with geogrid	~28	~15

There are generally two options to analysing the interaction geogrid-soil in the shear mode.

The first (more precise one) is to compare the shear strengths with/without geogrid for different normal stresses, the second one – to compare the parameters of the "Coulomb's envelope" φ and *c* with/without geogrid.

For the first option, let us define a "shear strength ratio" $f_g(\sigma)$ at peak shear strength as follows:

$$f_g(\sigma) = \frac{\tau^{\max}(\sigma)}{\tau_s^{\max}(\sigma)} \qquad (1)$$

where

$\tau^{\max}$ is the soil-geogrid peak shear strength and
$\tau_s^{\max}$ is the soil-soil peak shear strength.

Figure 8 presents the "shear strength ratio" envelopes for the geogrid with cemented and non-cemented soil. In all cases the value is about 1. Especially for the cemented soil, which case is the main issue herein, the values are >1.0 for the full range of normal stresses, indicating the suitability of the grid used for reinforcement of cemented cohesive soils.

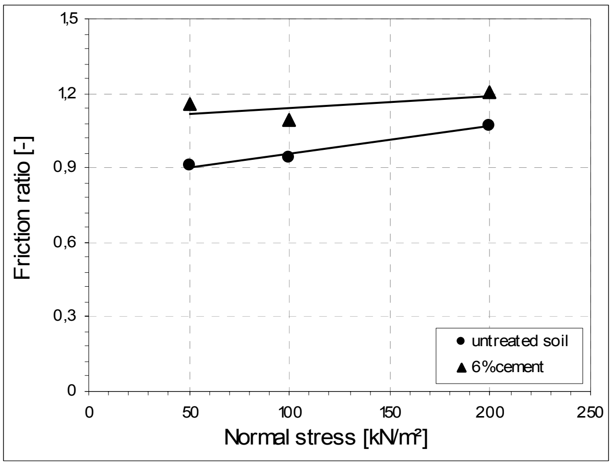

Figure 8 Friction ratio envelopes

For the second option, often the “coefficient of interaction for friction” CIF and the “coefficient of interaction for cohesion” CIC are being introduced, where CIF = tan φ with grid / tan φ, and CIC = *c* with grid / *c*. Note, that this option is not definitely correct, because φ and *c* are never constant but depend on normal stress. Due to that, the “shear strength ratio” mentioned above is the more correct criterion (Fig. 8). Nevertheless, Table 6 contains the CIF’s and CIC’s for a rough orientation only.

Table 6 Coefficients of interaction for friction CIG and for cohesion CIC for the geogrid tested

	Coefficient of interaction for friction	
	CIG [-]	CIC [-]
for non-cemented clay	~1.20	~0.53
for cemented clay	~0.92	~1.07

6 FINAL REMARKS

During the last decades there is an increasing shortage of traditional “good” non-cohesive soils as foundation and as construction material. Soft cohesive soil deposits are problematic soils for construction, thus they have been ignored or avoided for a long time. Today this is practically no more possible due to economic and environmental reasons. Some limitations could be overcome with the introduction of new construction techniques (Pinto et al., 2003).

For the aforementioned reasons, the performance of a new combined soil improvement technique, namely cement stabilisation with embedded PVA-geogrid, was investigated. A comprehensive laboratory testing programme was carried out. Unconfined compression, Proctor and shear tests were conducted with a cement content varying from 3% to 9%, resulting in the 6%-option to be the best one in that case. The study focused on the interface shear behaviour in the geogrid contact area, which knowledge is essential for stability analysis of geosynthetic structures. A recently developed novel testing device (see below) was used.

First results are presented, showing the shear behaviour of a typical “poor” cohesive soil without and with cement stabilization and without and with geogrid. The main issue was the behaviour of the combination cemented soil-geogrid because of the lack of knowledge for such cases combined with doubts about the shear strength, shear stiffness etc. in the interface zone geogrid-cemented soil.

It was found out, that the opposite is the case (at least with the PVA-geogrid used): the shear behaviour in the interface with geogrid is better both from the point of view of strength and strain. A positive synergetic effect seems to take place.

An appropriate design of soil reinforcement with geosynthetics requires among others a better understanding of the compound shear behaviour of the reinforced soil, using new last-generation testing devices with negligible influence of the device itself on test results. Such a new shear- and pull-out device has been developed and successfully used in this study, ensuring correct boundary conditions for both shear and pull-out tests.

Due to the lack of place only some of the first results (shear mode) are presented herein, which are believed to be important. The testing program is going on.

7 ACKNOWLEDGEMENT

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