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Determination of pull-out strength and interface friction of geosynthetic reinforcement embedded in expanded clay LWA

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ABSTRACT
The determination of the interaction between geosynthetic reinforcement and granular soils is one of the key factors in the design of mechanically stabilised earth structures. Only a few experimental investigations dealing with the interaction of geosynthetics and expanded clay LWA can be found in literature. Large-scale pull-out tests were carried out in order to determine the interface coefficient of friction and the pull-out strength under low normal load in the framework of the development of a new type of geotechnical structure. The project was undertaken to design and evaluate a reinforcement product embedded in expanded clay LWA 10/20 mm. Three different geosynthetics were tested under low normal loads using an anchorage box. Geosynthetics of two meters length and one meter width were embedded between two 40 cm thick expanded clay LWA layers. The samples were instrumented with displacement transducers distributed along the sample. A force transducer enabled the measurement of the pull-out force. The tests have shown a direct relationship between the geosynthetic products of opened or closed geometry and the diameter of the expanded clay LWA grain size (10/20mm) on the obtained pull-out force. Considerably higher anchorage strength and interface coefficient of friction are obtained for geosynthetic products of opened geometry (geogrids). Also the influence of geosynthetic stiffness on the pre-peak pull-out behaviour is discussed in the paper. The observations also suggest that the obtained results on a narrow particle size distribution are not necessarily transferable to conventional soils.

Keywords: MSE structure, expanded clay LWA, geosynthetics, pull-out tests, interface coefficient of friction

1 INTRODUCTION TO TEMASI

The research project TeMaSi deals with the development of a new type of retaining wall namely a mechanically stabilized earth structure, also called MSE Structure. In the scope of the study the combination of geosynthetics and expanded clay lightweight aggregates is considered. The present well-developed technique of geosynthetic soil reinforcement and parallel development of alternative construction materials as expanded clay LWA gives good possibilities to combine these two materials in geotechnical engineering. This offers an innovative solution to classical retaining walls, as for example rigid or modular gravity walls. The new developed structure is composed of geosynthetic tubes stacked on each other and anchored with geosynthetic reinforcement in the expanded clay LWA backfill (Figure 1). The new proposed structure offers in comparison to the classical solution a number of advantages.

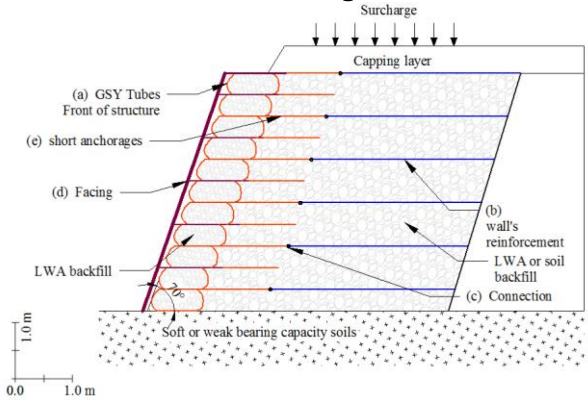


Figure 1. Cross-section of innovative geotechnical structure.

Expanded clay LWA aggregates gives the possibility for rapid construction (blow in place) and can be combined with geosynthetics to be filled into long continuous geosynthetic tubes. The unit weight of the filling material contributes to a significant reduction of the gravity weight of the entire structure. As a consequence, the construction of the new structure is interesting in areas where soft and compressible soils are considered. A significant reduction of total and differential settlements can be achieved. In the scope of the research project a new developed filling system the so called Low Pressure System is introduced to provide a uniform and continuously filled geosynthetic tube (Górniak, 2013). The control of filling density and the shape of the geosynthetic tube, enables to obtain a pre-defined facing part of the structure without the use of any scaffolding. The behaviour of the geosynthetic tubes under normal actions (Gorniak *et al.*, 2015) and combined vertical and lateral actions simulating the earth pressure effect have been studied experimentally and numerically. In the year 2010 and in year 2012 geotechnical structures had been constructed. It was demonstrated that the developed filling system is very efficient and less time consuming than other construction method of existing retaining walls. A total time of six minutes is needed to fill a thirty meters long geosynthetic tube. Moreover numerical studies of the geosynthetic tubes have provided useful results and a better comprehension of the new type of structure (Górniak, 2013).

As it was shown in Figure 1, the geosynthetic tubes are anchored in the backfill of the structure by help of long geosynthetic reinforcements. To provide an optimal design of the geosynthetic reinforcements, qualitative information about the interaction of geotextiles or geogrids and the mobilising shear strength are necessary for the optimal design of a reinforced earth structure. The study presented in this article aims with the measurement and the determination of the pull-out strength, as the interface coefficient of friction of the expanded clay LWA and three geosynthetic products (woven geotextiles and geogrids).

2 INTRODUCTION TO EXPERIMENTAL TESTING: PULL-OUT TESTING

During the last decade, the knowledge of geosynthetic - soil interaction under pull-out testing has become well known in geotechnical engineering. Numerous experimental studies large scale pull-out devices (Moraci & Recalcati, 2006; Palmeira, 2004) developed for the study of geosynthetic-soil interaction and numerical studies (Huang *et al.*, 2011; Tran *et al.*, 2013) demonstrated the importance of several factors affecting the bearing and pull-out strenght of the reinforcement. Also experimental analysis of shear interface tests between geosynthetics and LWA have shown high interface friction angles (Bakeer *et al.*, 1998b; Karri & Reis, 2009; Valsangkar & Holm, 1990). However, the application of non-classical filling soils as expanded clay LWA aggregates in interaction with geosynthetic reinforcement requires additional studies to permit a better comprehension of the interaction phenomenon. Accordingly to the properties of the filling soil (infrequent granulometry 10/20 mm and considerably lower than by classical soils bulk density 350 kg/m^2) the characterisation of the pull-out resistance and interface friction coefficient was conducted under moderate effective stresses and large size specimens. The study considered the development of an optimal reinforcement product, that could be adapted to any required reinforcement length and geometry.

2.1 Experimental studies of expanded clay LWA interaction with geogrids

During the last decade the investigation of geosynthetic properties considered as reinforcement of classical soils stayed noticeable. Numerous research works (Bakeer *et al.*, 1998a; Bakeer *et al.*, 1998b; Delmas, 1979; Moraci & Recalcati, 2006; Palmeira, 2004; 2009; Yuan *et al.*, 2002) had been performed, starting with simple pull-out apparatus and ending up with complex and well developed devices. Those principles have been also introduced into geosynthetic reinforced lightweight aggregate structures, where the soil develops considerable large anchor strength and interface friction (Jenner *et al.*, 2008; Watn *et al.*, 2008). In the literature the expanded clay LWA-GSY interaction, should be more investigated because of its infrequent grain size and grain shape. Moreover, a more particular attention should be given to the possible limited compressive strength of those materials and the crushing resistance. Nevertheless, those materials offer in comparison to classical soils numerous advantages: their high internal friction angle ϕ'=35 - 38°, resistance to oedometric loading R = 0.48 - 0.6 N/mm², low bulk density 350 kg/m^3 and fast and easy procedure of installation and compaction in the field (Watn, 2001; Wood & Høva, 2009).

Carried out pull-out tests demonstrated high anchor strength at various effective stress levels for embedded geogrids in LWA 0/10 mm (Bakeer *et al.*, 1998b; Yuan *et al.*, 2002) and in LWA 4/20 mm (Forsman & Slunga, 1994). The results of the studies of Yuan *et al.* (2002) and of Bakeer *et al.* (1998b) are set in Figure 1. Both of the authors applied various normal stresses to the specimen and both concluded, that the length of the geosynthetic influences the mobilised interface friction between the reinforcement and the LWA and the bearing resistance. This could explain, the higher resistance of the reinforcement tested by Yuan *et al.* (2002) at vertical stress equal to 31 kPa in comparison to the one tested by Bakeer *et al.* (1998b) at normal stress equal to 60.4 kPa. Note that the inclination of the force-displacement curve is very gentle. This may be an indication for the possible rolling of LWA grains along the reinforcement and considerable displacements mobilised between the geosynthetic reinforcement and the LWA.

Clear discrepancy is observed when increasing the normal load for the two various lengths. The interface friction coefficients obtained in the testing are set in Figure 3. Please note that Yuan et al. (2002) considered for his calculation the residual friction angle and cohesion of LWA, as the surface of the embedded geogrids, not the length of the embedded reinforcement as (Bakeer *et al.*, 1998b).

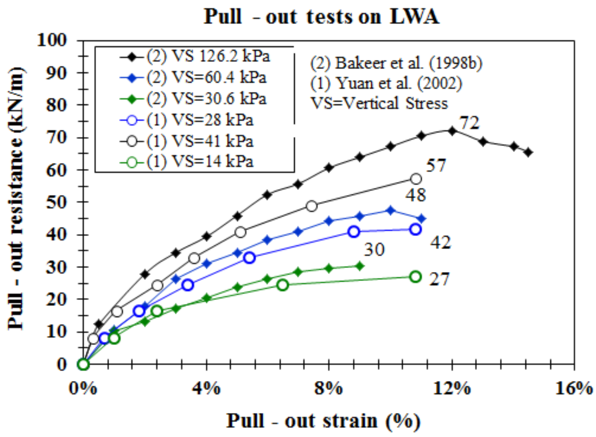


Figure 2. Pull-out strength versus pull-out strength of Bakeer et al. (1998b) et Yuan et al. (2002).

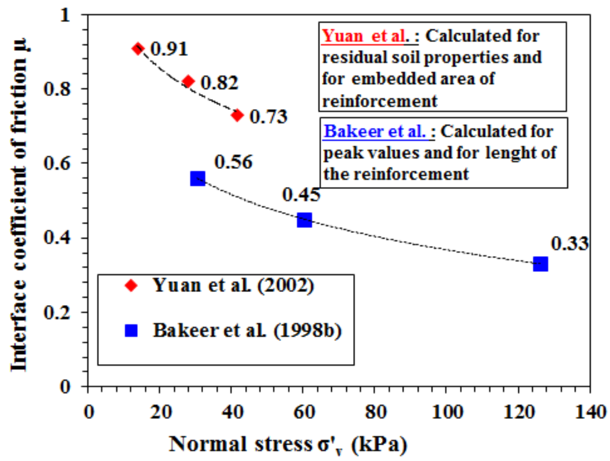


Figure 3. Results of pull-out tests: Pull-out resistance for various levels of normal stress performed by Yuan et al. (2002) and Bakeer et al. (1998b).

Also the peak values of soil properties were introduced in their calculations. Thus, the

values can't be compared directly from the chart.
Mentioned parametric and geometric factors that establish the pull-out behiour of the extensible products has to be optimised for the 10/20mm expanded clay LWA.

3 TEMASI – EXPERIMENTAL RESEARCH ON PULL-OUT STRENGTH

3.1 Testing apparatus and instrumentation

The testing apparatus, as described also in Brainçon (Briançon, 2001), is a steel framework device composed of four beams and pillars supplemented with wooden boards (plywoods). The apparatus has a length of 2.5 m, width of 1.2 m at the external sides and 2.45 m long and 1.15 m at the inside as in Figure 4.
Two meters long samples can thus be freely tested in the apparatus and be embedded at various depths in the apparatus up to 1.5m height. The pull-out load is provided by the manually operated pulley fixed to a steel and rigid frame. The frame is additionally fixed to the slab by screws. Additionally, to avoid friction between the testing material and the surface of the wood, plastic films are clamped at the sides of the box. The load application speed can be chosen between slow and fast and is controlled by the number of rotations of the pulley and equals approximately v_t = 5 mm/min.
The geotextile is hold by help of a steel clamp (Figure 4), that has the width of the fabric and enables to overlap the specimen around its circumference. At the clamp device a force transducer is installed that can provide the pull-out force. It is important to determine the displacement along the reinforcement using displacement LVDTs placed directly on the diagonal along the specimen. The obtained measurements are recorded by help of a data logger and enable the transfer of the results to a PC. The normal load is applied by help of steel plates (one package of steel plates represents a normal load of 3.69 kPa). The steel plates are placed on a transition layer a 12 mm thick wooden plate that enables the application of normal loads on the whole testing surface.

3.2 Testing materials

Tested geosynthetic products are presented in Table 1. All the products are warp knitted geotextiles produced of two various polymers: high tenacity polyester and polypropylene. The mechanical properties of these geotextiles have been tested in the laboratory in accordance to the actual standard (NF-EN-ISO-10319).
The product A is a knitted geogrid with rectangular mesh (size of the openings approx. 80x40 mm) . Its ultimate tensile strength is 130 kN/m in the direction of the pull-out force, and 60 kN/m in the transverse direction. The elongation at break of product A equals ε = 11 %. The two other products, product B and Product C, are warp knitted geotextiles.

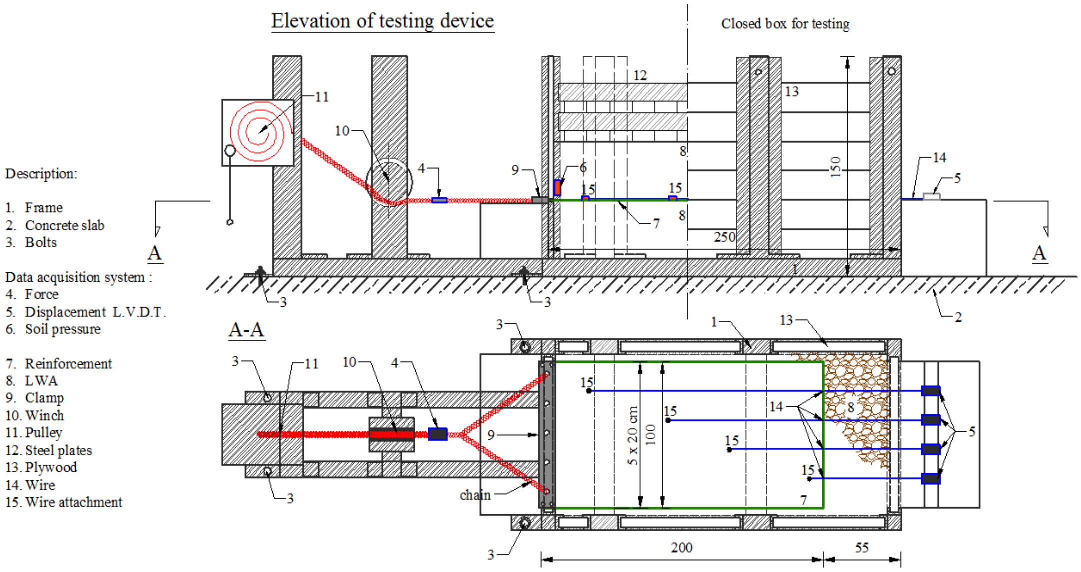


Figure 4 Testing apparatus after (Briançon et al., 2008)

Product B of tensile strength 150 kN/m in the length direction with significantly smaller opening sizes 3 x 3 mm. Product C has no openings. The properties of the other products are given in Table 1. Note, that product B and product C had the same axial strength but different stiffness, hence they are produced either from polyester or polypropylene.

Table 1 mechanical properties of tested geotextiles and geogrids

Label/ Polymer Tensile strength MD x CD	Opening size [mm]	*R* [kN/m]	*ε* [%]	*J* [kN/m]
A Polyester 130 x 130	80 x 40	130	11	1500
B Polyester 150 x 50	3 x 3	150	11	2300
C Polypro-pylene 150 x50	no open-ings	150	16	1100

Tensile strength R, elongation at break ε and stiffness J of the products are given in the Machine Direction (pull-out direction).

Properties of tested expanded clay LWA are set in Table 2. Physical and mechanical properties of expanded clay LWA have been investigated in laboratory testing in a research project (Wood & Høva, 2009). Results are based on performed laboratory analysis at Sintef in a 150 mm diameter tri - axial apparatus. Please note, that the applied confinement of the tested samples was in the range of σ_3 = 20 - 80 kPa.

Table 2 properties of tested expanded clay LWA

State	Bulk density [kg/m^3]	Shear strength	
		At peak ϕ_p'°	Residual friction angle ϕ_{pr}'°
Loose 10/20 mm	320	34	34
Compacted 10/20 mm at 10%	350	38	38

In order to insure the sustainable functions of the geosynthetic products the geochemical degradation of the polymer in the environment of the soil has to be studied. The authors have performed first geochemical analysis (immersion tests) of expanded clay LWA in tap-water. At the beginning of testing, after two days of immersion, high pH-values > 10 were measured. After seven days of immersion a decrease in pH-values > 9 was obtained. The authors are aware that the performed tests should be improved, however for pH-values grater than 9 other polymeric products than the polyolefines (polypropylen, polyethylen) cannot be considered for the further development for this project. The tested polyester products serve only as experimental basis of products with higher geosynthetic stiffness (Górniak, 2013).

3.3 Experimental plan

The defined length of the sample equalled 2.0 m and the width 1.0 m. The prepared soil is covered by large plywood, sufficiently thick to disable deformations of the box and the exerted deformations at the frontal wall. Three different normal loads are applied by help of steel plates: 5.0 kPa, 8.9 kPa and 12.4 kPa. Every product was tested twice under the same configuration, which makes 18 tests in total. The tests were performed to 20 cm displacement at clamp. The experimental plan is presented in Table 3.

Table 3 performed number of tests

Number of performed tests	Product	Applied normal load (kPa)
6	A	5.0, 8.9, 12.4
6	B	5.0, 8.9, 12.4
6	C	5.0, 8.9, 12.4

4 ANALYSIS OF TEST RESULTS

4.1 Pull-out strength

Pull-out forces, measured for the tested extensible reinforcements vary according to the applied normal loads, their stiffness and lengths. The obtained results in this study demonstrated however, that the geometry (opening size) of the geosynthetic has an influence on the obtained initial stiffness and post-peak regime of the pull-out strength. The measurements obtained from the data acquisition system are represented for the first displacement transducer D-1, placed in the front of the sample plotted versus the measured pull – out force (see Figure 8). In Figure 5 the results of testing of product A, B and C at vertical stress σ_n = 8.9 kPa are presented, while in Figure 6 the results of testing at vertical stress σ_n = 12.4 kPa are presented.

At first, two different force-displacement responses of products can be observed from the plotted results. Globally, the geogrid (Product A) in comparison to the geotextiles (Product B and Product C) show likely a displacement-softening behaviour, with a progressive decrease in the pull-out strength after reaching a peak value.

In opposite, geotextiles with ‘closed’ structure have the tendency to maintain the pull-out resistance when reaching the peak; no abrupt decrease of the residual strength in this case is observed.

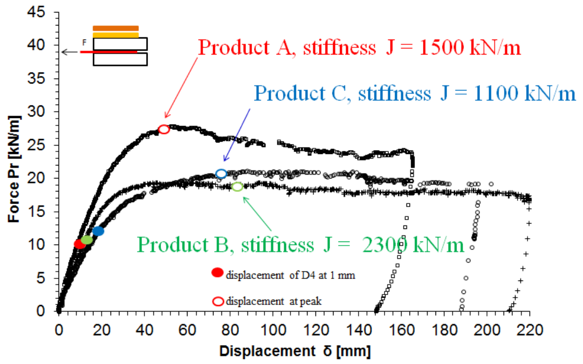


Figure 5 Pull-out force – displacement D1 tested at normal load σ_n=8.9 kPa for product A, B and C.

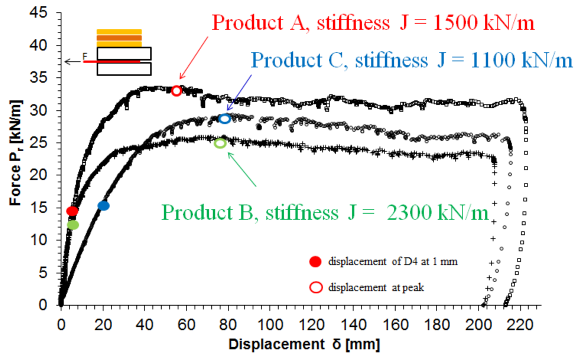


Figure 6 Pull-out force – displacement D1 tested at normal load σ_n=12.4 kPa for product A, B and C.

At the ultimate residual strength the reinforcement tend to slip between the embedded soil layers. This phenomenon is related to the aggregate – interaction in the pull-out box, where interface friction is affected by the aperture size and size of grains as demonstrated in Figure 7.

At second, the effect of product stiffness is clearly visible at the pre-peak region, so at the onset of loading (geosynthetic pulling) 20, 30 and 40 mm of displacement, where the stiffness of the product seem to play an important role.

During every test, the geotextile C has the tendency to undergo larger displacements as geotextile B. The stiffness of the pull – out force – displacement curve could be increased by a factor of two for the geotextile B for the range of two tested geotextiles (almost 1,5 bigger stiffness of geosynthetic). In case of comparable geotextile stiffness (product A and C), the stiffness of the pull-out force – displacement curve could be increased by a factor of around 1.2, for the range of two tested geotextiles.

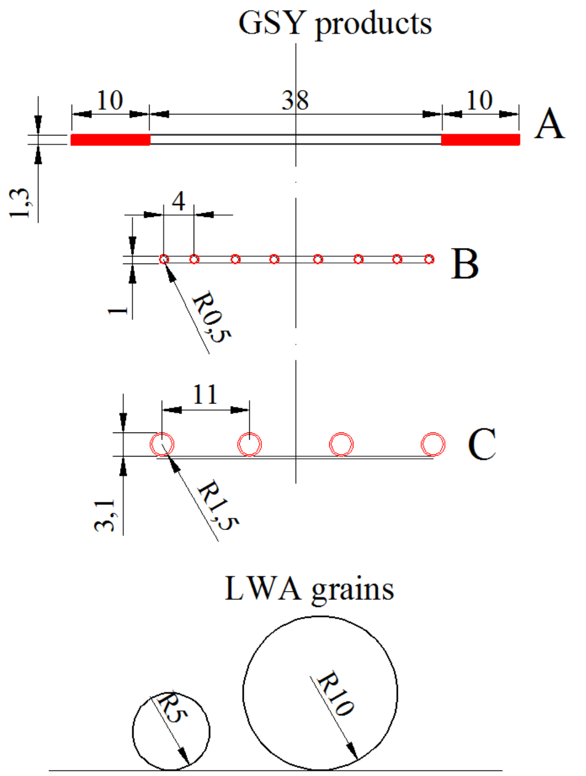


Figure 7 Geometry of tested geotextile products and size of LWA grains (min and max radius) in mm.

Please note, that also pull-out forces and displacements (see section 4.2) are mobilised differently along the whole length of the rein-

forcement showing a strong non-linear behaviour of tensile strain. The pull-out peak values under sequent normal loads of the products show similar tendencies, where pull-out resistances stay in similar ranges for geotextiles, while for "open" products, obtained peak values are 20 - 30% higher.
After reaching the peak values, the reinforcements tend to leave the box in a uniform manner (maximal clamp displacement 200 mm), maintaining the post – peak (residual) pull-out force at a constant level for product B and C. The apparent difference for product B and C despite lower stiffness of product C can be affected by the geometry of the product that enables the reinforcement sheet to achieve higher interface friction values. The steepness of the curve is developed accordingly to the stiffness of the reinforcement and the friction law. In Figure 7 the possible interaction was observed by the installation of the product on the LWA's first layer in the pull-out box. The case of product A represents packing and penetration of grains between the openings of the product, while B and C represent more a separation of the two layers than penetration. The former product can however enable better interlocking of smaller LWA grains (R_{grain} = 5 mm) between the longitudinal bars (distance = 8-10 mm) in comparison to product B. This might have been the reason why the post-peak strength of the product C exceeds the one of product B.

4.2 Pull-out displacements

The displacement transducers are located along the diagonal of the geosynthetic reinforcement at 20, 80, 120 and 180 cm distance (Figure 8).

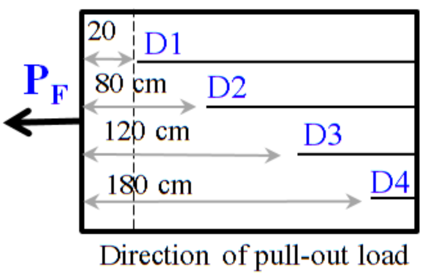
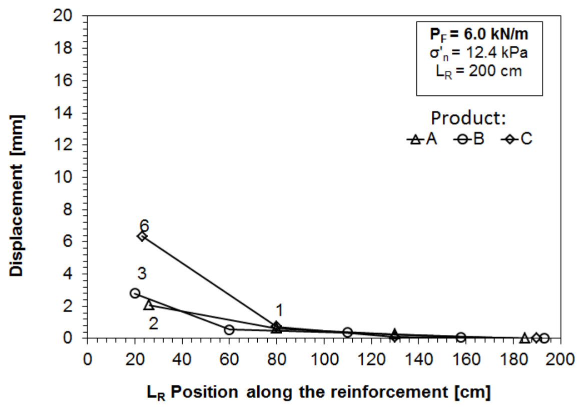
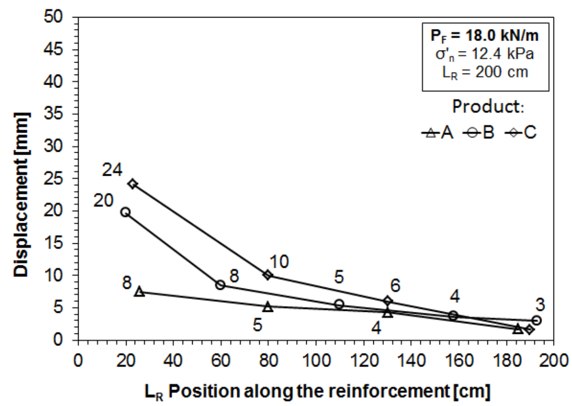


Figure 8 location of displacement transducers along the reinforcement.

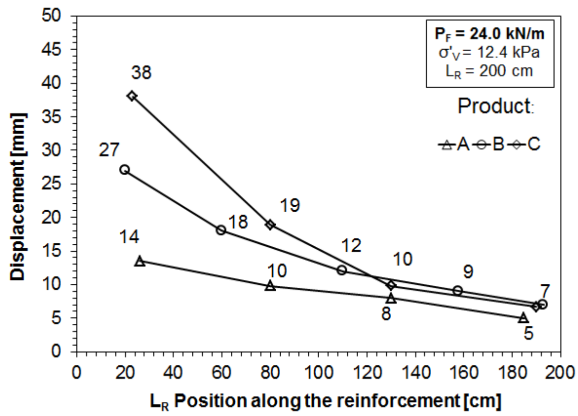
At a given pull-out force the values of displacements are represented along the 2.0 m samples for each position of the displacement transducer at normal stress σ_n = 12.4 kPa in Figure 9(a-c). The mobilisation of displacement is compared for all three products and takes place in a non-linear manner for each configuration along all marked nodes/points of the reinforcement in Figure 9(a-c).



(a)



(b)



(c)

Figure 9 Measured displacements along the geosynthetic reinforcements at (a) pull-out force 6 kN/m, (b) pull-out force 18 kN/m and (c) 24 kN/m

As can be observed from Figure 9 the less extensible product A has the tendency to reach rather simultaneously the mobilisation of displacements along its length responding

with relative small values of displacement in comparison to the products B and C.
Products represented by geotextiles, with more ‘close’ geometry, can be characterised by higher response to pull-out loading at the face of the apparatus and lower mobilisation in displacement at tail. At the pre-peak regime of the reinforcements, the stiffness of the products appears to play an important role before reaching its maximal value of shearing. It is even more remarkable for product C, while achieving higher pull-out forces.
Values of displacements at the onset of loading (where the displacements at tail are equal to 0 or 1 mm), confirm that the mobilisation of friction between the LWA grains and the reinforcement is reached as the tail of the reinforcement starts to displace. It can be seen as an important point of the interaction of the geogrids and geotextiles. At small values of displacements, the mobilisation of displacements becomes more favourable for product A and C, where the tail undergoes smaller displacements. As the pull-out force increases, the displacements of products B and C exceed the values recorded for product A. It can be said, that once the friction is mobilised along the whole reinforcement, geotextile grids are able to retain higher pull-out forces compared to geotextiles. In all cases in the pre-peak phase, the product C exceeds the values of product B.
Once the peak regime is reached, the embedded product continues to leave the confined zone of LWA uniformly increasing the values of displacements. In this phase, the displacements of each product become ‘parallel’ to each other and increase. Inversely, in comparison to the pre-peak region, the displacements at peak for product A become larger than for product B and C. At this point, the LWA - geotextile ensemble confined at three different normal stress values, where by increasing surcharge, contact forces between the grains and the reinforcement lead to uniform pull-out force. At this point the stiffness doesn’t play any role in the test and the reinforcement continues to slip between the soil layers.

4.3 Interface coefficient of friction

The interface coefficient of friction is calculated on the obtained result of the pull-out force. Values of pull-out forces can be compared to shear stresses mobilised at the interface for different normal loads applied to the samples and the embedded area of the reinforcement.
The estimation is made as following in Equation 1.

$$\tan\varphi_{soil/GSY} = \frac{P_i}{2.(L_R - D_i).B_R.\sigma'_v} \qquad (1)$$

where:
P_i - measured pull-out force at displacement D_i,
B_R - width of the tested reinforcement,
L_R - the embedded length of the sample,
D_i - measured displacement of the reinforcement of transducer D-1,
σ'_v - applied normal load.
From pull-out tests the coefficient $C_{i\Phi}$ is defined as follows in Equation 2 (NF-G38-064):

$$C_{i\Phi} = \frac{\tan\varphi_{LWA/GSY}}{\tan\varphi_{LWA}} \qquad (2)$$

The interface coefficients of friction $C_{i\Phi}$ are estimated for the internal friction angle at peak of the LWA defined under triaxial compression as $\tan\varphi_{LWA} = 0.78$ ($\varphi_{LWA} = 38°$). It is however necessary to mention, that the internal angle of friction is estimated for 10% of compaction by vibration of the soil. In the case of the anchorage tests and the field installation of the soil, the upper layers cannot be considered as compacted, thus smaller values of shear resistance should be considered.
In Table 4 the plotted values of $C_{i\Phi}$ and $\tan\varphi_{LWA-GSY}$ are represented for the three products versus the displacement D_i corresponding to the measurements of the displacement transducer D1.

Table 4 Values of interface friction coefficient of three tested products

Product	Width B_R (m)	Length L_R (m)	Internal friction angle $tan\varphi_{LWA}$ (-)	Interface coefficient of friction $C_{i\Phi}$ (-)
A	1.0	2.0	0.78	0.79
B	1.0	2.0	0.78	0.61
C	1.0	2.0	0.78	0.73

It could be easily said, that the values of the coefficient of friction should be considered as the design value of the LWA-geotextile for reinforced structures at the peak strength of the anchorage measured in the test. It is however not obvious with regard to the displacements of the reinforcement in the tests. For the tested products, the mobilised friction along the reinforcement, could be properly estimated when the reinforcement stays in the box and its tail is submitted only to negligible displacements. It is because, even when the peak strength was not entirely reached, the geotextile had started already to leave the box.

5 CONCLUSION

Large-scale pull-out tests are carried out on three different geosynthetics under three normal loads, using an anchorage box. Geosynthetic reinforcements of 2 m x 1 m dimensions are embedded between two 40 cm thick LWA layers. They are instrumented with displacement transducers distributed along the length of the sample. A force transducer enables the simultaneous measurement of the pull-out force. One earth pressure transducer is installed on the frontal wall of the box and records the increments in horizontal pressure.

The main objective is to test products with different opening geometries and apparent stiffness embedded in LWA to develop a reinforcement product of the MSE wall. The tests are carried out on one geogrid that can be considered as similar to the optimal product that needs to be developed for the MSE reinforcements. The remaining two products are tested to compare the behaviour of geogrids and geotextiles embedded in LWA.

The tests have shown the importance of opening size regarding the diameter of the LWA grains (grain distribution 10/20 mm).

A good design of the opening can naturally improve the interaction coefficient soil - geosynthetic. It is shown, that the integrated LWA grains inside the opened product achieve higher anchorage strength in comparison to products of closed geometry, for the range of tested products. Nevertheless, by providing useful information on the pre-peak behaviour, it opens the possibility to optimise the product to minimise the displacements at the service state.

The gained knowledge on the testing concerns also the experience made on the implementation method of LWA and its interaction with reinforcements. The way to fill the testing box with backfill is very easy and fast, in comparison to classical soils. The light LWA can be installed by blowing or by help of big shovels. The round grains of LWA facilitate the installation of products with openings between the layers. Products of very narrow or almost no openings don’t have the adaptability to interlock with the grains and will rather act by friction on both sides of the geosynthetic. It shall be noted, that in this case the local deformation created by the LWA grains pressure increases the pull-out strength similarly as in gravel materials. This observation can lead to optimisation of the implementation conditions for the future specifications of reinforcements in the LWA (low C_u ratio equal to 1.5), and is rather a positive argument for the use of products with optimised openings, where the grains can penetrate through the product. This statement also demonstrates the necessity to use products with ‘open’ geometry for a better optimisation of reinforcement lengths in a real structure. The statement is also confirmed by Watn *et al.* (Watn *et al.*, 2004).

Values of chosen geosynthetic stiffness appear to be adequately high to observe differences in anchorage behaviour. Additional tests should confirm these encouraging results. The choice related to the testing box (rigidity of box, testing velocity and pulling mechanism) should be reconsidered while employing higher values of normal stresses. It should be noted that these results on a narrow particle size distribution (10/20 mm) are not necessarily transferable to conventional soils.

More generally, it should be noted that today the standards enable to evaluate the material‘s parameters at break (e.g. pull - out force at peak or residual stresses). This study in terms of reached pull-out strength can provide useful information on the design of structures in particular the approach to assessing displacements.

6 ACKNOWLEDGMENTS

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