In-soil-testing of geogrids with low construction deformations

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ABSTRACT: For soil reinforcement with geosynthetics the comparison of the stress-strain behaviour of the soil and the geosynthetics is of great importance. Because the soil allows small deformations, the aim was to test different products, especially new developed laid geogrids, with high modulus shown by the tensile test results even at low strains. Pull-out tests and full scale model tests of a two layer miniature steep slope (MSS) were conducted under the same testing conditions for different geogrids and nonwovens for comparison purpose. The results show clear differences depending on the soil type and the production method of the geosynthetics. At the pull-out tests the maximum pull-out forces for the tested woven geogrid are only approx. half as large as for the tested extruded and the tested laid geogrid, although the products have nearly the same tensile strength. Especially at small displacements up to 10 mm in the pull-out tests, there were partially significantly steeper rises of the pull-out force/displacement curve for the extruded and the laid geogrid. This shows clear advantage on the soil interaction with these products at usage states of loading. The tendencies of the pull-out tests are also to be found at the MSS tests. The tested products with higher tangent modulus at the pull-out test show the smallest, the woven grid and the mechanically bonded nonwoven the highest deformations at the model slope.

1 INTRODUCTION

For soil reinforcement with geosynthetics the comparison of the stress-strain behaviour of the soil and the geosynthetics is of great importance. Because the soil allows small deformations, the aim is to develop products with comparable modulus to the soil.

For reinforcement with nonwovens among others McGown et. al. (1992), Bauer, Bräu (1994, 1996) showed that those products have quite different behaviours at tensile tests in air than in soil. The influence of the soil decreases using wovens or grids for reinforcement. Therefor it is important to use products with high modulus shown at the tensile test results even at low strains. Most of the known products show a great difference between the stress-strain behaviour of the reinforcing elements (fibres, yarns) and the final product. Further on product specific construction deformation is utilised after installation and creates additional deformation without load transfer. This leads to an inefficient utilisation of the strength of the reinforcing elements and results in unnecessary deformation at site within the geosynthetic-soil-composite.

A series of laboratory pull-out tests and full scale model tests simulating a two-layered steep slope were carried out with different soil and reinforcement types. The actual results are presented, although the series will be continued.

2 PULL-OUT TESTS

As pull-out tests and the interpretation of the results are topic of discussions for many years up to now, the following results are not intended to be used for calculations but for the comparison of different products under the same conditions.

2.1 *Test apparatus and execution*

A shear box with the dimensions l/b = 50 cm / 50 cm was used. The box consists of two soil containers with a height of h = 25 cm each. A general view is shown in Figure 1.

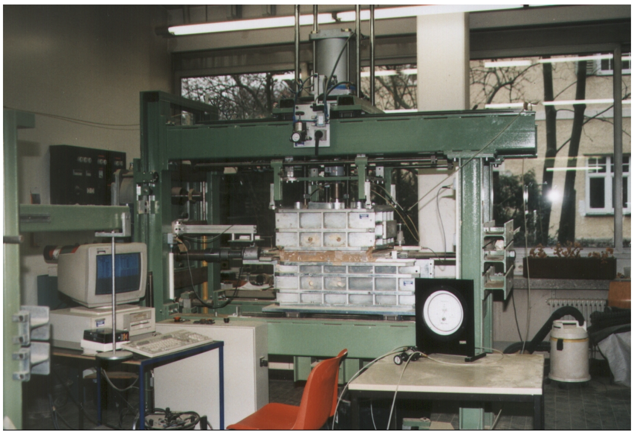

Figure 1. General view of the shearbox used for pull-out tests

At the height of the separation between the upper and the lower soil container, a clamping device for the geosynthetic specimen is arranged on the pull side. This clamping device can be moved away from the soil containers by an electro-motor with a constant rate of feed. The rate of displacement and the necessary force both are measured. In the tests, always a rate of displacement of v = 10 mm/h was used.

The lower box is filled with soil material up to the upper edge.

On this prepared soil the geogrid specimen to be tested was laid in such a way that the specimen lies centrally to the width of the shear box. On the tensile side, the specimen protrudes approx. 10 cm from the soil containers. On this side the specimen is stretched into the clamping device. On the opposite side the specimen also protrudes 10 cm. This ensured that during the whole test a constant specimen area was surrounded by soil.

Soil was filled into the upper soil container up to a height of approx. h = 15 cm.

After completion of the soil installation, two pressure cushions were installed between the soil and a cover plate. Over these pressure cushions the required normal stress was placed onto the geosynthetic/soil system.

The test series were carried out with three normal stresses (σ_N = 10, 40 and 80 kPa).

2.2 *Soil types used in pull-out tests*

For the series of tests two coarse-grained soil types were used. In Figure 2 the particle size distribution curves are shown.

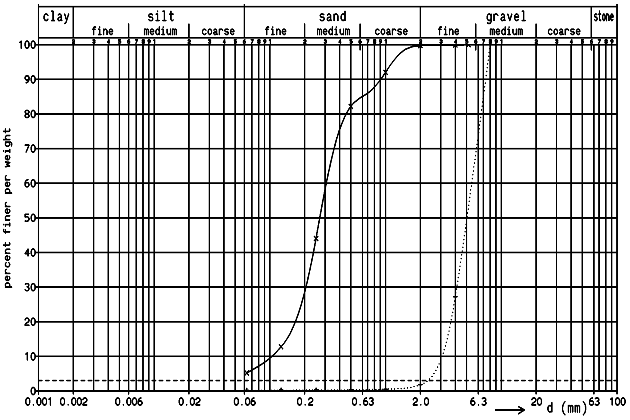

Figure 2. Particle size distribution of soils used in pull-out tests

2.2.1 *Sand*

The sand which was used has a maximum grain size of d_{max} = 2 mm through sieving. The portion d < 0.063 mm is 5 %. According to DIN 18196, it is a poor-graded sand (SE). According to DIN 18126, the minimum dry density is $\rho_{d,min}$ = 1.41 g/cm³, the maximum dry density $\rho_{d,max}$ = 1.70 g/cm³.

In the tests, the sand was installed in dry condition (water content w < 0.5 %) with a medium dry density (D = 0.5).

2.2.2 *Crushed stone*

The crushed stone which was used is a broken sharp-edged granite material with a maximum grain size of d_{max} = 8 mm. The portion d < 2 mm is 1.5 %. According to DIN 18196, it is an poor-graded gravel (GE).

In the tests the crushed stone was installed in a dry condition (water content w < 0.5 %).

2.3 *Products used in pull-out tests*

For the pull-out tests 3 different geogrid types were used. An extruded, a woven and a laid geogrid. The relevant characteristic values are shown in Table 1.

Table 1. Characteristic values of geogrids for pull-out test

Product	raw material	mesh size (mm)	tensile strength (MD, kN/m)	tensile strength (CD, kN/m)
extruded geogrid (EG1)	PP	39	30	30
laid geogrid (LG1)	PES	40	40	40
woven geogrid (WG1)	PES yarns, PVC coating	20	35	30

The laid geogrid is a new developed product that is assembled from flat bars made of PET black with a cross-section of 12 mm x 0.7 mm. The flat bars are bonded with each other at the crossing points through a special welding technique.

The woven and the extruded geogrid are well known products not to be described in detail. All 3 products are biaxial geogrids.

Different test series were conducted on the pull-out test. Besides the variation of the soil types, they mainly contained variants as to the geometry of the geosynthetic specimen. Some single longitudinal bars, two parallel longitudinal bars with and without single transverse bar were tested with the transverse bars partly being used with and without protrusion over the joints.

From the numerous tests the following results are about examinations on product specimens which always have two longitudinal bars (l = 70 cm) in the distance of the grid aperture and all transverse bars with a length up to the middle of the grid aperture following the longitudinal bars.

2.4 *Test results of pull-out tests*

The following Table 2 shows the results of evaluating the maximum pull-out force of the tests using sand and crushed stone.

Table 2. Maximum pull-out forces

Product	normal stress kPa	max. force kN	at displacement cm	force refered to product EG1 -	displacement refered to product EG1 -
			sand		
EG1	10	0.54	2.93		
	40	1.49	5.57		
	80	2.25	7.50		
WG1	10	0.31	2.36	0.57	0.81
	40	0.56	3.49	0.38	0.63
	80	1.18	4.62	0.52	0.62
LG1	10	0.60	3.57	1.11	1.22
	40	1.09	2.26	0.73	0.41
	80	1.98	1.46	0.88	0.19
			crushed stone		
EG1	10	2.12	9.21		
	40	2.39	5.09		
	80	2.41	4.43		
WG1	10	0.92	5.52	0.43	0.60
	40	1.26	6.24	0.52	1.23
	80	1.31	3.15	0.54	0.71
LG1	10	1.81	5.01	0.85	0.54
	40	2.21	3.01	0.92	0.59
	80	2.09	2.67	0.87	0.60

The results show that under the same conditions the EG1 reaches the highest values of the maximum pull-out force. WG1 only reaches about 50 % and LG1 about 90 % of these values for sand and crushed stone. The length at this force is shortest at the LG1 (about 60%, sand and crushed stone) and at about 70 % (sand) and 85 % (crushed stone) with the WG1.

The effect that LG1 has nearly the same maximum pull-out force than EG1 at only half the pull-out length could be studied more clearly when evaluating the forces at certain length. These values are shown in Table 3.

Table 3. pull-out forces at certain displacement

Product	normal stress	pull-out force at			refered to product EG1 at		
	kPa	1 mm	5 mm	10 mm	1 mm	5 mm	10 mm
		kN	kN	kN	-	-	-
sand							
EG1	10	0.18	0.39	0.48			
	40	0.25	0.69	1.00			
	80	0.27	0.81	1.18			
WG1	10	0.12	0.25	0.29	0.68	0.64	0.61
	40	0.14	0.35	0.46	0.55	0.50	0.46
	80	0.19	0.44	0.59	0.71	0.54	0.50
LG1	10	0.24	0.46	0.53	1.32	1.20	1.12
	40	0.40	0.98	1.04	1.62	1.41	1.04
	80	0.46	1.56	1.98	1.72	1.93	1.67
crushed stone							
EG1	10	0.25	0.75	1.17			
	40	0.25	0.86	1.36			
	80	0.28	0.95	1.42			
WG1	10	0.12	0.30	0.42	0.51	0.39	0.36
	40	0.13	0.32	0.49	0.53	0.37	0.36
	80	0.12	0.37	0.57	0.43	0.39	0.40
LG1	10	0.24	0.61	0.77	0.97	0.81	0.66
	40	0.31	1.05	1.54	1.26	1.22	1.14
	80	0.42	1.53	(2.10)	1.47	1.61	(1.48)

(...) product was broken immediately before reaching the displacement

The same tendencies are observed when calculating the tangent modulus at certain pull-out length. The values are listed in Table 4.

Table 4. Tangent modulus for pull-out test at certain displacement

Product	normal stress	tangente modulus at displacment		tangente modulus refered to product EG1	
		1 mm	5 mm	1 mm	5 mm
		kN/cm	kN/cm	-	-
sand					
EG1	10	1.11	0.28		
	40	1.75	0.79		
	80	2.28	0.93		
WG1	10	0.58	0.17	0.52	0.59
	40	0.89	0.31	0.51	0.39
	80	1.10	0.40	0.48	0.43
LG1	10	1.76	0.15	1.59	0.52
	40	3.38	0.31	1.93	0.39
	80	4.39	1.62	1.93	1.74
crushed stone					
EG1	10	1.90	0.95		
	40	2.25	1.14		
	80	2.41	1.21		
WG1	10	0.59	0.35	0.31	0.37

Product	normal stress	tangente modulus at displacment		tangente modulus refered to product EG1	
		1 mm	5 mm	1 mm	5 mm
		kN/cm	kN/cm	-	-
	40	0.65	0.35	0.29	0.31
	80	0.82	0.45	0.34	0.37
LG1	10	1.62	0.44	0.86	0.46
	40	3.14	1.16	1.39	1.02
	80	3.83	1.84	1.59	1.52

It is shown that the maximum pull-out forces for EG1 and LG1 are nearly equal, however the LG1 reaches them at lower pull-out length. The maximum pull-out forces of WG1 are only approx. half of those values, although the products have nearly the same tensile strength.

Especially in the beginning of the pull-out test, i. e. at small displacements up to 10 mm, there were partially significantly steeper rises of the pull-out force/displacement curve for LG1 compared to the other products. For comparable pull-out lengths there were higher tangent modules and thus accordingly also higher pull-out forces at LG1 compared to EG1. The product WG1 partly only reaches values less than 50 % of those of EG1.

It can be concluded that the soil interaction behaviour of the LG1 is similar to that of EG1 and both have advantages in the considered items compared to WG1.

3 FULL-SCALE MODEL TESTS

For studying the geosynthetic/soil-interaction in a full scale model test, several two-layered “miniature steep slope” (MSS) were built and loaded. Although it is no direct simulation of a real steep slope, using the same conditions for all the products gives clear advice on the different behaviours.

3.1 *Construction and execution*

The tests were carried out in the testing pit of the Institute for Soilmechanics and Foundation Engineering of the Technical University Munich. Figure 3 shows a cross section of the MSS construction.

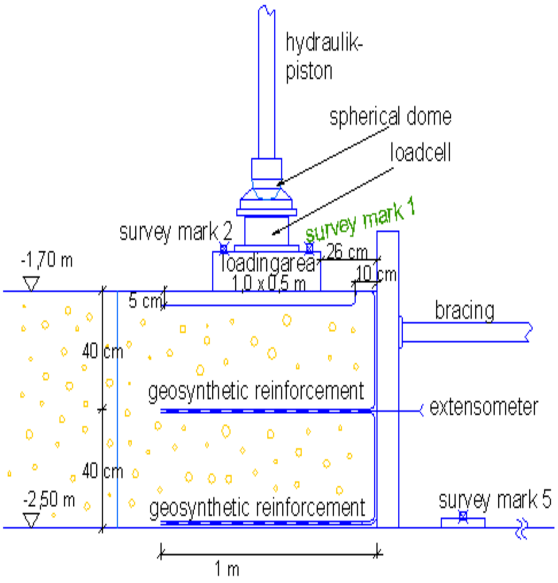

Figure 3. Cross section of MSS

The test pit is filled with compacted sand described in 3.2.1. For the tests with gravel the sand in the base of the MSS was replaced with 30 cm of gravel.

The construction consists of two soil layers (h = 40 cm each) where the geosynthetics were wrapped around at the front. Between the two soil layers the products lay in direct contact without connection. The reinforcement length is 1 m.

The construction is 1 m wide with the sideway boundaries made of wooden plates with smooth coated surface. The boundaries were backfilled with sand to prevent deformations and reach a plane deformation status of the MSS.

The loading area consists of a rigid steel construction with 1 m width (same as MSS) and 0.5 m in length direction. The loading is done by a hydraulic piston with interlayered spherical dome and load cell.

For installation a vertical formwork is used. The geosynthetics are placed, the soil layers filled and compacted by a vibrating plate compactor and the reached densities checked.

After completion of installation the formwork is removed and measuring marks are placed on the front to follow the horizontal deformations and on top for the vertical deformations. Additionally between the two soil layers 4 extensometers are fixed at the geosynthetics to check the strain.

The loading is done in several steps each documented with measuring results. The deformations increasing to much or being not possible to raise the load anymore, the test were stopped. It was difficult to fix a definite maximum bearing capacity, because usually there was no clear failure of the MSS. This was a problem for the test, but is of course an advantage of those constructions.

Figure 4 shows a MSS at a loading stage of 850 kPa with the associated deformations.

Figure 4. miniature steep slope at loading step σ = 850 kPa

3.2 *Soil types used in pull-out tests*

For the series of tests two coarse-grained soil types were used. In Figure 5 the particle size distribution curves are shown.

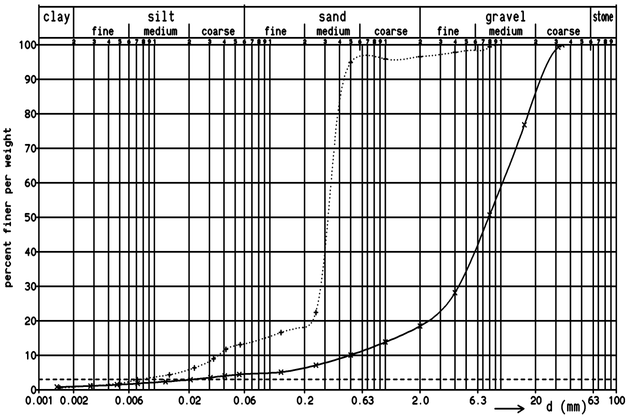

Figure 5. Particle size distribution of soils used in full-scale model test

3.2.1 *Sand*

The sand which was used has a maximum grain size d_{max} = 10 mm through sieving. The portion d < 0.063 mm is 12 %. According to DIN 18196, it is a poor-graded sand (SE). According to DIN 18126, the minimum dry density is $\rho_{d,min}$ = 1.41 g/cm³, the maximum dry density $\rho_{d,max}$ = 1.70 g/cm³.

In the tests, the sand was installed with water content 7 % < w < 9 % with a medium dry density between ρ_d = 1.55 and 1.65 t/m³.

3.2.2 *Gravel*

The used gravel is a round shaped quarzitic material with a maximum grain size of d_{max} = 32 mm. The portion d < 2 mm is 18 %. According to DIN 18196, it is a well-graded gravel (GW). This gravel is usually used as natural aggregate for concrete production.

In the tests the gravel was installed with water content 3 % < w < 4.5 % with a medium dry density between $\rho_d = 1.95$ and 2.15 t/m^3.

3.3 *Products used in MSS*

For the MSS tests 3 different geogrid types, 1 mechanically bonded nonwoven and 1 thermally bonded nonwoven were used. The relevant characteristic values are shown in Table 5.

Table 5. Characteristic values of geogrids for MSS test

Product	raw material	mesh size (mm)	tensile strength (MD/CD, kN/m)	strain at failure (MD, %)
extruded geogrid (EG2)	PP	115	55	11
laid geogrid (LG2)	PES	40/40	60/60	7
woven geogrid (WG2)	PES yarns, PVC coating	23/23	55/30	12.5
mechanically bonded nonwoven (MNW)	PES	---	18	65
thermally bonded nonwoven (TNW)	PP	---	12/12	70

EG2 is an uniaxial geogrid. The LG2 is assembled from flat bars made of PET black with a cross-section of 8 mm x 0.95 mm.

3.4 *Test results of MSS*

3.4.1 *Maximum loads*

The following Table 6 shows the maximum loads of the tests carried out.

Table 6. Maximum loads and vertical deformations of MSS

No	soil	geosynthetic	test final state		
			max. load (kPa)	max. settlement (cm)	geosynthetic was
1	sand	WG2	830	28.3	
2	sand	LG2	960	26.3	
3	sand	EG2	1080	25.9	
4	gravel	WG2	1330	10.35	ruptured
5	gravel	LG2	1580	8.65	
6	gravel	EG2	1600	11	ruptured
7	gravel	---	330	1.2	
8	gravel	MNW	1460	11.5	ruptured
9	gravel	TNW	1710	24.6	ruptured

These results show that MSS with gravel have higher failure loads and less settlement than those with sand. Within the gravel tests the effect of reinforcement is quite obvious comparing No.7 (unreinforced gravel) with the other tests. Slightly surprising are the failure loads for MNW and TNW in the same range as with geogrids but with higher deformations, especially in horizontal direction (see 3.4.3).

3.4.2 *Settlement of loading plate*

Besides the maximum loadings the development of the settlement is of interest. In Figure 6 the settlement of the loading plate is shown.

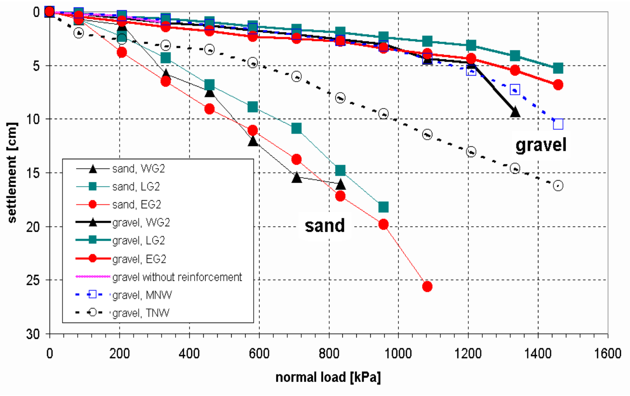

Figure 6. Settlement of loading plate at MSS tests

The curves in Figure 6 show clear differences between the tests with gravel and sand. Differences of the various geosynthetics within one soil type seem to be not evident, nevertheless the order of deformations is LG2 < EG2 < WG2 for gravel and sand. Although all tests were carried out under same conditions, the test result of TNW is special and has perhaps to be considered in further tests.

3.4.3 *Horizontal deformations*

The horizontal deformations are measured along a vertical line in the middle of the construction. Following the loading steps it was found that the tests with WG2 had already great deformations at lower load levels, which occurred from one step to the other. The absolute deformations were within the range of the MNW. The deformations of EG2 and LG2 tests had a continuous and similar development at lower and medium load levels. At higher load levels the EG2 has higher values of deformation. For all products the deformations with sand are 5 – 6 times higher than those with gravel.

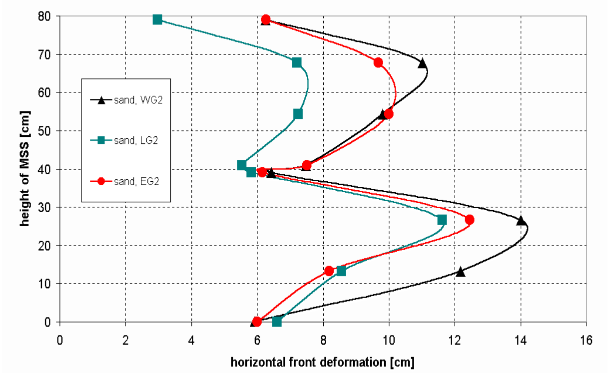

Figure 7. Horizontal deformations of MSS tests (sand, σ = 850 kPa)

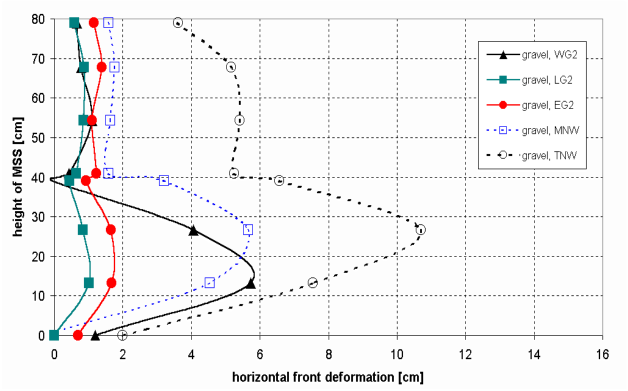

Figure 8. Horizontal deformations of MSS tests (gravel, σ = 850 kPa)

There are results for all loading steps (Floss et. al. 2000) but for comparison it seems best to look at the horizontal deformations at a certain load for all tests. For loading σ = 850 kPa Figure 7 shows the results for MSS tests with sand and Figure 8 those with gravel.

For MSS tests with sand the horizontal deformations are similar for all 3 products with the smallest deformations at the LG2.

For MSS with gravel great differences are between the LG2 and EG2 tests and the tests with the other products. While LG2 and EG2 tests show a parallel movement of the front, the WG2 and the nonwovens have great deformations at the lower layer. The range of deformations at WG2 is the same as with MNW.

For sand and gravel tests the horizontal deformations are in following order LG2 < EG2 < WG2.

Additionally in Table 7 and 8 mean values of the horizontal deformations are given for all tests at certain load levels. The tendencies shown in the above figures also can be found at the other load levels.

Table 7 Mean horizontal deformations of MSS tests with sand

	mean horizontal deformations (cm) at load (kPa)		mean horizontal deformation referred to LG2 at load (kPa)	
	450	850	450	850
LG2	3.2	7.0		
WG2	5.6	9.1	1.75	1.30
EG2	4.4	8.3	1.38	1.19

Table 8 Mean horizontal deformations of MSS tests with gravel

	mean horizontal deformations (cm) at load (kPa)			mean horizontal deformation referred to LG2 at load (kPa)		
	450	850	1200	450	850	1200
LG2	0.1	0.7	1.15			
WG2	0.5	1.7	7.3	5.00	2.43	6.35
EG2	0.6	1.2	2.3	6.00	1.71	2.00
MNW	0.6	4.5	5.2	6.00	6.43	4.52
TNW	1.2	6.3	10.9	12.00	9.00	9.48

3.4.4 *Strain in medium geosynthetic layer*

At the geosynthetic layer between the two soil layers 4 extensometers were fixed. Calculating the differential length this allows to give strains for 3 sections. In Table 9 and 10 values for the middle section are given for the MSS tests.

Table 9. Mean values of strain (middle section, sand)

	mean strain (%) at load (kPa)		mean strain referred to EG2 at load (kPa)	
	450	850	450	850
EG2	2.1	8.4		
LG2	2.4	7.0	1.14	0.83
WG2	5.2	8.4	2.48	1.00

At the test with sand the strain for WG2 is at the low load level with more than 5% twice as high than at the others. At the higher load level the values are similar again. Although values of 7 to 8 % are reached which are in the range of strain at failure for some products, no damage or plastic deformations were found at excavation.

Table 10. Mean values of strain (middle section, gravel)

	mean strain (%) at load (kPa)			mean strain referred to LG2 at load (kPa)		
	450	850	1200	450	850	1200
LG2	0.9	1.8	2.1			
WG2	0.1	0.7	8	0.11	0.39	3.81
EG2	0	1.5	3.3	0.00	0.83	1.57
MNW	0.6	2.1	7	0.67	1.17	3.33
TNW	2.1	15	33	2.33	8.33	15.71

The tests with gravel show according to the very small deformations at the front also low values of strain. Only the TNW has significant values that increase to values of more than 30 %.

The LG2 and EG2 have values of 2 to 3 % even at the highest load level, whereas WG2 has values similar to the MNW.

At maximum loads for most products the strains reached failure states which led to ruptures that were found at excavation. Only with LG2 strain values of about 3 % at σ = 1600 kPa were measured and a visually undamaged product was found at excavation.

4 CONCLUSION

For soil reinforcement with geosynthetics the comparison of the stress-strain behaviour of the soil and the geosynthetics is of great importance. For reinforcement with nonwovens the only possibility to get more realistic design values is to test the products load-strain-behaviour in soil. As the influence of the soil decreases using wovens or grids for reinforcement, it is important to use then products with high modulus shown at the tensile test results even at low strains. Most of the known products show a great difference between the stress-strain behaviour of the reinforcing elements (fibres, yarns) and the final product. Furtheron product specific construction deformation is utilised after installation and creates additional deformation without load transfer. This leads to an inefficient utilisation of the strength of the reinforcing elements and results in unnecessary deformation at site within the geosynthetic-soil-composite. As a consequence the development of new types of geosynthetic reinforcement is in progress and led to a laid geogrid made of crossing PES bars, that is used in the presented tests.

Pull-out tests and full scale model tests of a two layer miniature steep slope (MSS) were conducted under the same testing conditions for different geogrids and nonwovens for comparison purpose. The results show clear differences depending on the soil type and the production method of the geosynthetics.

At the pull-out tests it is shown that the maximum pull-out forces for woven geogrid (WG1) are only approx. half as large as for the extruded (EG1) and the laid geogrid (LG1), although the products have nearly the same tensile strength.

Especially in the beginning of the pull-out test, i. e. at small displacements up to 10 mm, there were partially significantly steeper rises of the pull-out force/displacement curve for EG1 and LG1 in comparison to WG1. For comparable lengths there were higher tangent modules and thus accordingly also higher pull-out forces. This shows clear advantage on the soil interaction with EG1 and LG1 at usage states of loading.

The tendencies of the pull-out tests are also to be found at the MSS tests. The products with higher tangent modulus at the pull-out test show the smallest, the woven grid (WG2) and the mechanically bonded nonwoven the highest deformations at the model slope.

Overall a comparison test with a not reinforced slope (gravel) showed the high reserves of bearing capacity of geosynthetic reinforced systems with announcing failure mechanism instead of sudden crashes of systems with soil only. The high levels of loadings (up to 1500 kPa) in the MSS tests are in congruence with the experience of field loading tests (Bräu et.al. 2000).

The values which have been presented here are from comparing tests showing tendencies and allowing conclusions to be drawn based on the knowledge of the behaviour of known products in actual structures to the behaviour of other products. Instead of loadings of full scale steep slopes these tests give the possibility to check more parameters in less time saving money. Further tests are planned combined with measurements and backanalysis of “real” structures.

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