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Field and Laboratory Tests on the Bearing Behaviour of Unpaved Roads Reinforced by Different Geosynthetics

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ABSTRACT: Field experiences have shown that the use of geosynthetics improves the trafficability of unpaved roads on soft subsoil. Specifically, the thickness of the base course and therefore the amount of high quality geomaterials e.g. crushed gravel can be reduced. Until now, the design is mainly based on empirical approaches based on results from experiments obtained in field tests. The thickness of the base course is increased until an adequate bearing capacity of the unpaved road is reached. There are extensive studies throughout the literature that confirm the mechanism of the bearing capacity improvement, but mostly cover only individual effects such as the influence of the bearing layer thickness at constant subsoil strength. Therefore, they cannot be extended to a general theory and design approach that can account for all of the important variables. To investigate the effectiveness of different geosynthetics in unpaved roads a series of loading tests on geotextile reinforced, unpaved roads were carried out both in the laboratory and in the field. Beside the bearing strength and stiffness of the soft subsoil, the base course thickness as well as the type, and hence the strength of the geosynthetics were varied in the tests. This paper presents a brief summary of the experimental results that may be used to evaluate models to predict the bearing capacity of unpaved roads.

KEYWORDS: Geosynthetics, Soil Reinforcement, Experiments, Unpaved Road, Soft Soil, Base Course, Cyclic Loading

1. INTRODUCTION

The bearing capacity of unpaved roads is mainly influenced by the type of material used for the base course, the thickness, the kind of installation and its compaction, the strength of the subsoil and the interaction between the subsoil, geotextile reinforcement and the base course. In the literature a plethora of tests are documented. In most of the test series either boundary conditions were not clearly described or only particular geotextile products were examined. Moreover, in the experimental approach, by far too many influencing parameters were varied within a single test series and therefore results do not allow to find a suitable theoretical design model. In previously carried out research, some of the main influencing parameters controlling the effectiveness of geosynthetics in unpaved roads were examined in detail (Bräu and Vogt 2011). Important results and the main conclusions of the research work are presented in this paper. A brief numerical analysis of the geotechnical boundary value problem in question was undertaken, with the method of finite elements. This was conducted with the goal of identifying the decisive parameters controlling the effectiveness of various types of geosynthetics and as a basis for a series of small-scaled loading tests. The findings of the laboratory tests were extrapolated to full scale loading tests and field tests including traffic loads, which were then analysed.

2. SMALL SCALED LOADING TESTS

2.1 Test device

To examine the fundamental factors of a geosynthetic reinforced unpaved road a small-scaled test model was set up. The test device (depicted in Figure 1) was designed following the preliminary finite element study predicting the influence of boundary conditions such as the anchor length of the reinforcement layer and the dimensions of the test tank.

A layer of soft soil (subsoil) was inserted within a testing chamber with a diameter of 50 cm. On top of the soft subsoil a layer of geosynthetic was placed and then a statically compacted base course. Using a load piston (of diameter 5 cm), static and cyclic loading was applied. The settlement of the load piston and the deformations of the base course were monitored. Additionally, in some tests pore water pressures were measured within the soft subsoil.

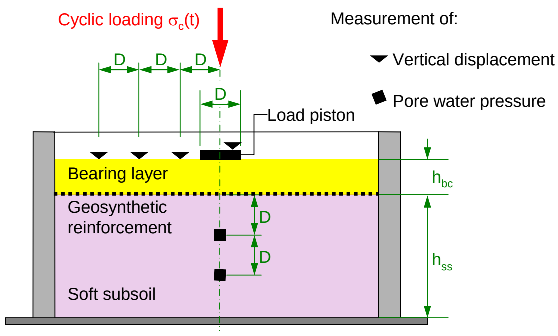

Figure 1 Setup of the model scaled loading tests

2.2 Placement of the soft subsoil

For each loading test the fine grained soft subsoil was mixed up and subsequently filled homogenously, without air bubbles to a minimum thickness of h_{ss} = 20 cm. The properties of the soft soil are given in Figure 2. To facilitate placement of the subsoil the sample was mixed at a water content of 80 M.-%, roughly twice the water content at liquid limit w_L. The high water content also limits the amount of undesired air bubbles within the soil if carefully pumped into the testing chamber.

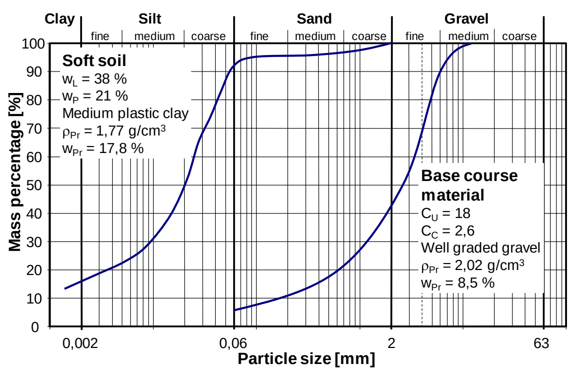

Figure 2 Soft soil and base course material used in the model scaled loading tests

In the testing chamber the subsoil was consolidated until end of primary consolidation was reached (at least about 2 days) under static load using a rigid steel plate. The squeezing of the soil at liquid consistency was prevented by using O-ring seals at the rigid steel plate. The consolidation stress was varied in order to obtain a certain undrained shear strength s_u. By this method it is possible to achieve a homogenous density, water content and shear strength. This was checked before the loading tests by measuring the undrained strength s_u using a small vane shear test apparatus and the water content w. These properties, in addition to the dry density ρ_d and void ratio respectively were also measured after the loading test.

The soft soil providing the subsoil in the model scaled tests can be characterized as a medium plastic clay with a water content at the liquid limit of $w_L = 38$ % and plastic limit of $w_P = 21$ %. For the normally consolidated state, shear vane tests and a number of triaxial compression tests give a ratio between the vertical consolidation stress σ'_v and the undrained shear strength of roughly $s_u / \sigma'_v = 0.3$. The angle of friction lies at around $\varphi' = 28$ °, while cohesion can be neglected ($c = 0$) due to the triaxial tests results for the normally consolidated clay. The compression index C_c is estimated to be roughly 0.25, with a swelling or recompression index C_s of about 1/6th of the compression index C_c.

The base course material is a well-graded crushed gravel including about 7 M.-% of fines < 0.06 mm in diameter (Figure 2). The angle of repose was found to be approximately 40 °.

2.3 Geosynthetics and base course material

In accordance with the small-scaled loading test conditions, including geometrical and force scaling, a grid-like geosynthetic (GT-1) and a non-woven geosynthetic (GT-2) were choosen whose mechanical strength and stiffness are considerably lower than that of geosynthetics used in field conditions (Table 1).

Table 1 Parameters of model type "Geosynthetics"

	Tensile strength [kN/m]		Elongating at failure [%]	
Direction	md	cmd	md	cmd
GT-1 (grid-like)	19.6	12.8	2.9	2.6
GT-2 (non-woven)	1.9	2.7	18.0	33.0

md: test sample cut out parallel to machine direction during manufacturing (machine direction)
cmd: test sample cut out perpendicular to the machine direction during manufacturing (cross machine direction)

After consolidation of the soft soil the geosynthetic was placed firmly on top of the smooth surface of the subsoil.

The base course material (Figure 3) was placed with a homogenous water content of $w = 5$ M.-%. The base course was compacted to a dry density of $\rho_d = 1.85$ g/cm^3 by a loading plate under a defined load for 2 minutes. The short duration of the loading ensures that there is no further consolidation and thus, strength gain of the cohesive subsoil. The base course thickenss was defined relative to the diameter of the loading piston and varies between 0.5 D and 1.5 D.

2.4 Test procedure

The main output quantity used for the evaluation of the test series was the bearing capacity of the soft subsoil alone. Hence, several tests were conducted by loading the soft subsoil without the base course material. In these tests, the undrained strength s_u of the soft soil was varied by changing the consolidation pressure. Later, experimental tests on unreinforced and reinforced bearing layers were carried out.

Figure 3 Loading on top the surface of the base course

There were two types of loading in the model scaled tests. First, a static load with a constant rate of deformation was applied. The bearing capacity was defined as the medium stress under the loading piston, measured at a settlement of 20 mm or s / D = 0.4.

Second, sinusoidal cyclic loading was applied of a number of tests, with a loading stress that was varied between 5 kPa and 105 kPa at a frequency of 1 Hz. For evaluating the test results the settlement at 100 000 cycles was recorded.

2.5 Static loading test

As an example, the static bearing capacities q_s of the test series where the geosynthetic GT-2 was used are shown for different base course thickness of 0.5 D, 0.75 D, 1.0 D und 1.5 D, with an undrained shear strength of the soft soil between $s_u = 5$ kPa and 35 kPa.

The test results, depicted in Figure 4, show that for low base course thickness (0.5 D) there is little improvement of the bearing capacity, independent of the used geosynthetic. For a base course thickness at least 0.75 D large, and especially for low subsoil strengths, the bearing capacity increases considerably. Furthermore, it can be seen that for higher shear strengths, $s_u = 30$ kPa and above, the increase to the bearing capacity is marginal.

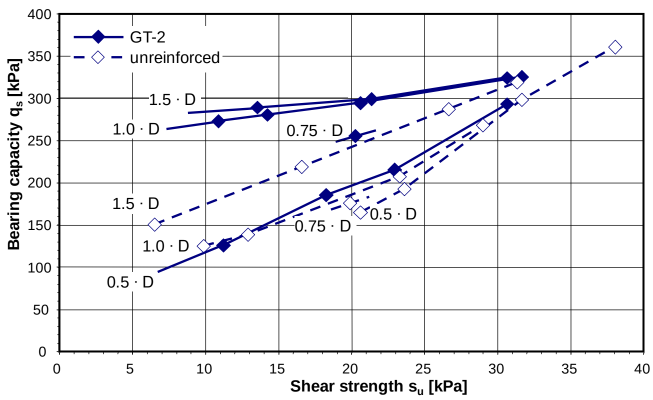

Figure 4 Results of the static loading tests featuring the geosynthetic GT-2

Increasing the thickness of the base course greater than $h_{bc} > 1.0$ D was found to give no further increase to the bearing capacity. Table 2 shows the bearing capacity achieved, with an undrained strength of $s_u = 20$ kPa and a factor of strength gain due to the non-woven geosynthetic GT-2.

Table 2 Static loading, bearing capacity q_s at s_u = 20 kPa

Height of bearing layer h_{bc}	Bearing capacity q_s		
	Unrein-forced	Reinforced GT-2	Factor of increase
0.50 D	155	195	1.3
0.75 D	175	255	1.5
1.00 D	185	290	1.6
1.50 D	240	300	1.3

2.6 Cyclic loading test

Under the same conditions (subsoil strength, base course thickness and used geosynthetics) as the static loading tests, cyclic loading tests were conducted.

The results shown in this paper are based on the relative settlement s/D measured at the load piston after 100000 cycles. For the unreinforced bearing layers the test results are given in Figure 5. Similar to the behaviour in the static loading tests the unreinforced systems are show a reduction in the measured settlement for base course thickness of 0.75 D or more.

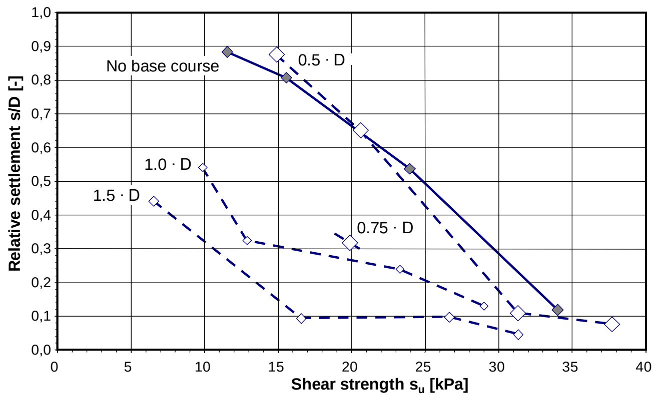

Figure 5 Settlement of the load piston after 100000 cycles, unrein-forced systems

With a base course thickness of 0.5 D, the bearing capacity is equal to what was measured on the soft subsoil itself. In this case the use of geosynthetics in between the soft subsoil and the base course the leads to a considerable reduction of the settlement under cyclic loading (Figure 6).

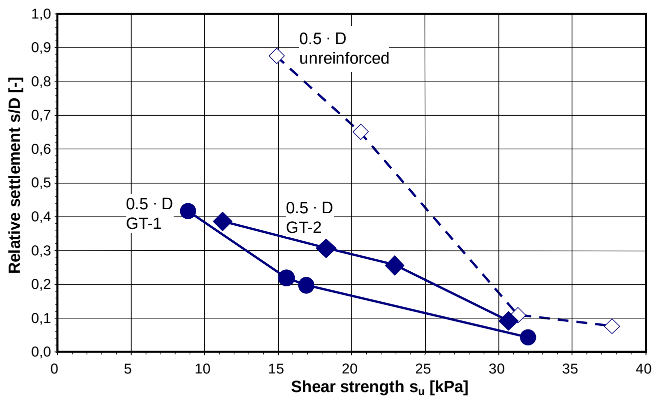

Figure 6 Settlement s / D of the model footing after 100000 cycles at a base course thickness of 0.5 D

The application of the rigid grid-like GT-1 results in a further settlement reduction compared to the more flexible and soft non-woven geosynthetic GT-2. The influence of the geotextile reinforcement decreases with increasing undrained subsoil strength, until approximately s_u = 30 kPa, where no further effect is visible

Table 3 tabulates the relative settlement s / D for a base course thickness of h_{bc} = 0.5 D and a subsoil strength of s_u = 20 kPa. At this base course thickness and subsoil strength the effectiveness of a geosynthetic layer in the model scaled test was found to be maximised. The experiments show that even usage of a low tensile strength (GT-2) geosynthetic leads to a 57 % reduction in settlements, compared to the un-reinforced case. The stiffer grid-like geosynthetic GT-1 was even found to reduce the settlement by 75 %.

Table 3 Comparison of the results at s_u = 20 kPa, h_{bc} = 0.5 D

System	Height of base course h_{bc}	Relative settlement s / D	Settlement reduction
unreinforced	0.5 D	0.67	-
reinforced GT-1		0.17	75 %
reinforced GT-2		0.29	57 %

At subsoil strengths higher that s_u = 30 kPa the influence of both base course thickness and geosynthetic reinforcement noticeably decreases ($\Delta(s / D) < 0.1$). This is clearly indicated by the small values of s / D, recorded in Table 4.

Table 4 Results of the cyclic loading tests using the non-woven geosynthetic GT-2

Subsoil strength s_u	Base course height h_{bc}	Relative settlement s / D
10	0.5 D	0.40 *)
	1.0 D	0.20 *)
	1.5 D	0.15 *)
20	0.5 D	0.28
	1.0 D	0.16
	1.5 D	0.13
30	0.5 D	0.10
	1.0 D	0.06
	1.5 D	0.04

*) extrapolated values

3. LARGE SCALED LOADING TESTS

3.1 Test setup

Unpaved roads reinforced by geosynthetics are built mainly for temporary site traffic and for low priority roads such as rural roads and forest trails. This situation was simulated through the usage of a large scale test pit, with an area of 3.3 m by 5.0 m, with placement of the subsoil, the geosynthetic reinforcement and the base course as shown in Figure 7.

Static and cyclic loads were applied to the surface of the bearing layer by means of a circular and rigid steel plate (diameter D = 300 mm). The resulting time and cycle were recorded, as well as the varying pore pressure in the soft subsoil. The test setup and the location of the transducers are shown in Figure 7.

3.2 Subsoil material, preparation and installation

A low plasticity clay was used for the soft subsoil material, a by-product of a nearby plant producing aggregates for road construction. This obtained clay was found to be very homogenous, with an almost constant water content. The plasticity and the grain size distribution are shown in Figure 8.

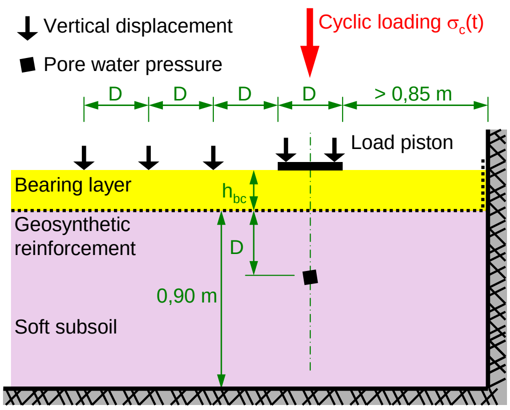

Figure 7 Large scale static and cyclic loading tests

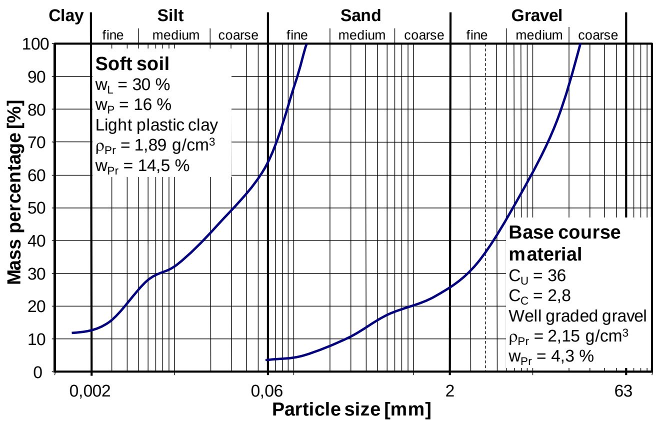

Figure 8 Soft soil and base course material used in the large scaled loading test

The light plastic clay can be described by an angle of friction φ' = 30 ° and a compression index of about Cc = 0.2. Triaxial tests where not performed on the soil due to the introduction of airvoids during compaction that influence both strength and stiffness. The soft soil was characterised by measuring s_u through vane shear tests after compaction, and after the loading tests were completed.

The clay was installed in 3 layers with a water content of 18 M.-% each compacted with a sheep foot roller (tamping roller, 1500 kg). The full thickness of the subsoil was about 0.9 m.

After compaction, the density ρ and the water content w were determined in a 1 m by 1 m grid as well as the undrained shear strength s_u (vane shear test). The tests showed a very low change in the results from shear strength s_u and water content determination.

3.3 Geosynthetics and base course material

The reinforcement layers considered were a non-woven (GT-3), a geogrid (GT-4) and a compound material (GT-5), consisting of the previously mentioned products (GT-3 and GT-4, Table 5).

The base course material was a well graded gravel with rounded grains that was placed to thickness from 0.5 D (150 mm) to 1.5 D (450 mm, Figure 9). The water content of the base course was 5 M.-% for each test setup and dynamic compaction was achieved in 4 passes with a vibratory plate of 140 kg weight.

The compacted state of the gravel base coarse material was measured by dynamic and static plate load tests as well as by determination of the density. The angle of repose of the loose gravel was found to be in the range of 45 ° to 50 °. These values were validated by a small series of triaxial compression tests, at a proctor density of ρ_{Pr} = 1,89, the angle of friction was found to be around or even higher than 50 °.

Table 5 Parameters of Geosynthetics used in large scale tests

	Tensile strength [kN/m]		Elongating at failure [%]	
Direction	md	cmd	md	cmd
Non-woven GT-3	6.5	10.0	50	30
Geogrid GT-4	40.0	40.0	8	8
Compound material GT-5	40.0	40.0	8	8

Figure 9 Subsoil installation for the large scale tests

3.4 Cyclic loading

Table 6 shows the parameters for the different test setups. The type of reinforcement, the thickness of the base course and the shear strength of the subsoil were varied.

Table 6 Test parameters examined in the cyclic loading tests

Reinforce-ment	Shear strength of subsoil s_u [kPa]	Base course height h_{bc}	Cyclic loading $\sigma_{c,max}$ [kPa]
none	30	0.5 D	350
			450
		1.0 D	450
			550
		1.5 D	550
GT-3	30	0.5 D	350
			450
		1.0 D	450
			550
		1.5 D	550
GT-3	60	0.5 D	350
			450
		1.0 D	450
			550
		1.5 D	550
GT-4	30	0.5 D	350
			450
		1.0 D	450
			550
		1.5 D	550
GT-5	30	0.5 D	350
			450
		1.0 D	450
			550
		1.5 D	550

Cyclic loading defined by $\sigma_{c,max}$ (Figure 10) was applied with values of 350 kPa, 450 kPa and 550 kPa. Since no large deformations occurred during the test, a total of 100000 cycles were applied with a frequency of 0.3 Hz. To understand the behaviour of the static and dynamic bearing capacity both types of loadings were conducted, however the results of the static loading are not shown in this work.

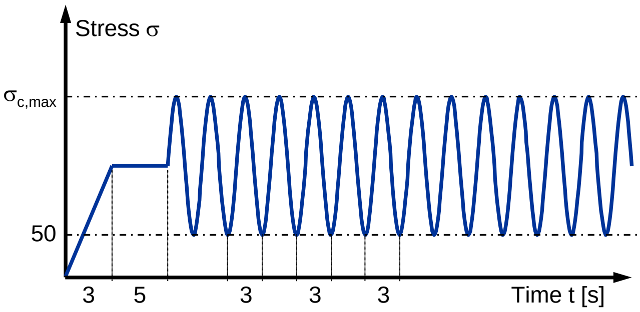

Figure 10 Cyclic loading

In this report the results of four test regimes are discussed, consisting of an unreinforced system and systems with the reinforcement layers GT-3, GT-4 and GT-5. The base course thickness varied between 0.5 D and 1.0 D and the cyclic loading stress $\sigma_{c,max}$ between 350 kPa and 550 kPa. Figures 11 to 13 show the settlement normalized by the diameter of the loading plate (s / D) plotted against the number of cycles.

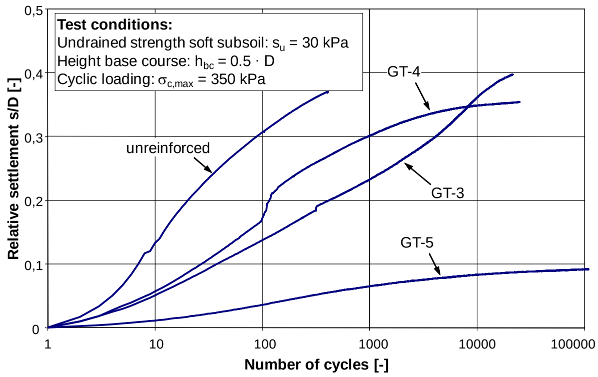

Figure 11 Cyclic loading $\sigma_{c,max}$ = 350 kPa, s_u = 30 kPa, h_{bc} = 0.5 D

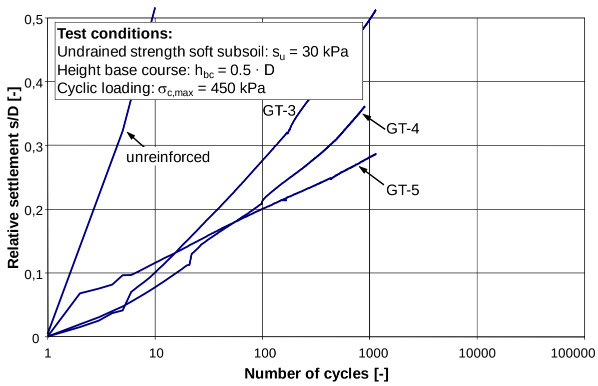

Figure 12 Cyclic loading $\sigma_{c,max}$ = 450 kPa, s_u = 30 kPa, h_{bc} = 0.5 D

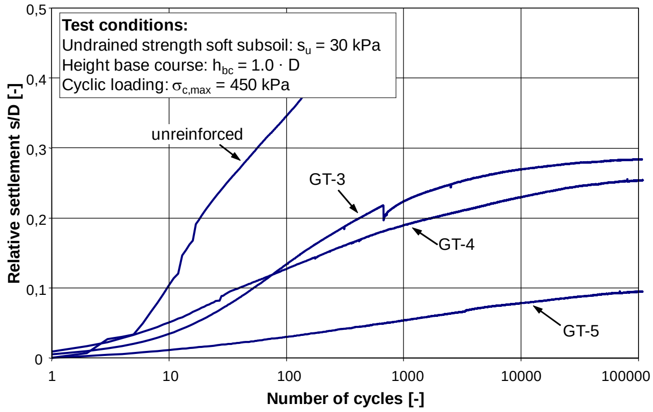

Figure 13 Cyclic loading $\sigma_{c,max}$ = 450 kPa, s_u = 30 kPa, h_{bc} = 1.0 D

Figures 11 to 13 show that at a small base course thickness of h_{bc} = 0.5 D (150 mm) and a moderate loading ($\sigma_{c,max}$ = 350 kPa; Figure 11) there is little difference between the GT-3 and GT-4 products and a significant increase in performance of all systems in comparison to the unreinforced case. Furthermore, there was a significant settlement reduction for the product GT-5.

Increasing the load ($\sigma_{c,max}$ = 450 kPa, Figure 12) and keeping all other boundary conditions constant result in increased deformations of the compound product, GT-5 as well. Under higher loads and a low base course thickness all products can be seen to behave similarly.

Considering a loading of 450 kPa and increasing the base course thickness to h_{bc} = 1.0 D = 300mm; Figure 13) shows again the benefit of the compound material. The difference between the other two products (GT-3 and GT-4) is negligible.

With a further increase in the cyclic loading stress of $\sigma_{c,max}$ = 550 kPa (see Figure 13), and with the other conditions kept constant, the non-woven (GT-3) fails after a small number of cycles. The stiffer products GT-4 und GT-5 show a better performance and similar deformations at low cycles. This change with higher numbers of cycles where the compound material presents a slightly better behaviour than the geogrid alone.

A summarising graph showing the settlements at n = 1000 cycles, with the majority of test results is given in Figure 14.

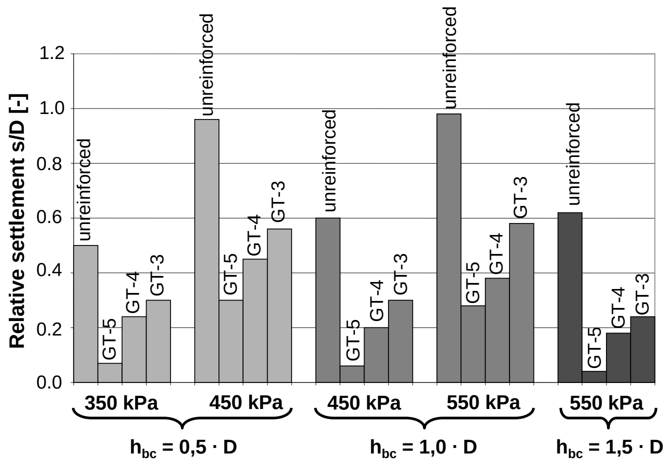

Figure 14 Summary of the relative settlements (s/D) after n = 1000 cycles with a subsoil undrained shear strength s_u = 30 kPa

4. FIELD TESTS

4.1 General

Tests under field conditions were conducted in order to verify the experimental results from small and large scaled loading tests. The field tests were set up next to a railway construction site where an unpaved road was used by loaded trucks delivering bulk freight for nearby construction measures. This trucks gave the loading of the test setup.

The characterisation of the bearing behaviour of the subsoil as well as of the reinforced unpaved granular base course was done by the use of static plate loading tests. The in-situ bearing behaviour of the subsoil was found to be much stiffer than that of the subsoil in the experiments in the laboratory presented in section 2 and 3 respectively. Hence, the ability to identify the differences in the bearing behaviour arising from the use of different geosynthetics was very limited. The influencing parameter of the base course thickness was varied in the field test. Firstly, tests were performed on a base course thickness of about 30 cm, increasing to roughly 60 cm in a second phase of the experiments. For this thickness, the rut depths were measured after about 2000 passes of loaded trucks.

The surface of the subsoil was tested using static and dynamic plate loading tests. The results from the dynamic plate loading tests are given by the dynamic deformation modulus E_{vd} according to ASTM E2835 – 11 (German TP BF-StB part 8.3.). The deformation modulus from static plate load tests are given by E_{v1} (first loading) and E_{v2} (second loading). ASTM D1194/1195/1196 (German DIN 18134) defines the specifications of the static plate load test.

The obtained results lead to the conclusion, that the subsoil alone without any base course layer may be sufficiently loaded by at least a few number of passes by trucks during dry weather conditions. Nevertheless, it is clear that the low to medium plastic clayey subsoil is sensitive to water infiltration and a larger reduction in the bearing capacity and trafficability is to be expected after rainfall.

4.2 Description of the test site and subsoil

The test field was situated adjacent to a stretch of unpaved road, an area previously used for agricultural purposes. The top soil layer of approximately 40 cm removed (see Figure 15), and the exposed surface, to which the geosynthetics were later to be placed, was examined by measuring the in-situ water content and determining the liquid and plastic limit of the subsoil. Furthermore, static and dynamic plate loading tests were also conducted.

Figure 15 Preparation of the test site

The subsoil consists of a low to medium plastic clay including a small fraction of sand and gravel particles. For the experiments presented in section 2 und 3 the undrained shear strength was directly determined using a vane shear test apparatus. This was not possible in the field however, as the sand and gravel particles disturb the penetration and rotation of the vane shear apparatus strongly. Hence, the undrained shear strength s_u was indirectly found by using a correlation from the consistency index I_C after determination of the in-situ water content, the water content at liquid w_L and the water content at plastic limit w_P. The measured range of the water content at the liquid limit is from w_L = 41 % to 49 %. The water content at the plastic limit was found to be in between w_P = 18 % and 24 %. According to the natural water content the consistency index of the subsoil ranged from I_C = 0.9 to about 1.0. From these values the undrained shear strength can be estimated to be in the range of s_u = 140 kN/m^2 to 190 kN/m^2 seems to be reasonable taking into account that to subsoil was rather disturbed by the agricultural purposes and therefore without strength rising from soil structure.

The data from the measured natural water content and plasticity together with the results from the conducted plate load tests give a detailed description of the subsoil conditions, which are comparably homogenous within the length of the test site (Figure 16).

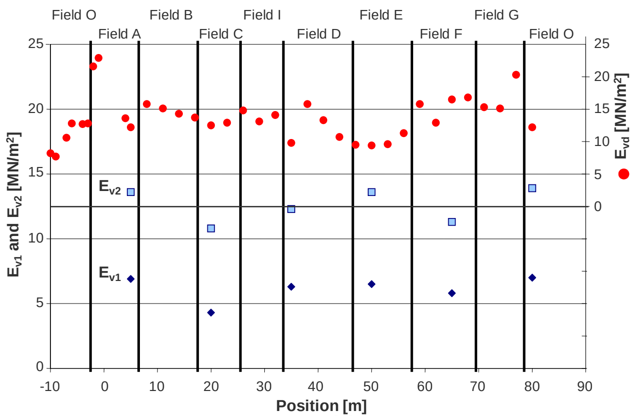

Figure 16 Tests results from static (modulus first loading E_{v1} and modulus reloading E_{v2}) according to German DIN 18134 and ASTM D1194/1195/1196 respectively as well as results from dynamic plate load tests by E_{vd} according to German TP BF-StB part 8.3 and ASTM E2835 – 11 respectively on subsoil

4.3 Geosynthetics and base course material

In accordance with the construction plans the 4 m wide unpaved road was to be constructed by placing a woven polypropylene geosynthetic of robustness class GRK 3 (see Table 7) on top of the subsoil, with a gravel base course thickness of 60 cm.

For research proposes instead of the GRK 3 class woven geosynthetic different types of geosynthetics and a temporary base course thickness of about 30 cm were installed over a length of 100 m. After conducting the first phase of field tests the base course thickeness was further increased to about 60 cm (second phase). The compaction of the gap graded gravely base course material, with predominantly rounded grains, was carried out by the usage of a conventional 14-ton heavy vibratory roller.

The various test fields configurations, defined by the different types of geosynthetics are listed in Table 8. Field O at the beginning and at the end of the test site contained the polypropylene geosynthetic of robustness class GRK 3 in accordance with the construction plans of the unpaved road. Alternative products to the woven polypropylene geosynthetic of Field O that are typically used for building unpaved roads were placed in Field B and C.

Table 7 Definition of robustness classes (GRK) for geosynthetics according to the German TL Geok E-StB 05 and M Geok E

Robustness class	Non-woven geosynthetics		Woven geosynthetics	
	Static puncture $F_{p,\,5\%}$ [kN]	Mass per unit area $m_{A,\,5\%}$ [g/m²]	Tensile strength $F_{5\%}$ [kN/m]	Mass per unit area $m_{A,\,5\%}$ [g/m²]
GRK 1	≥ 0.5 kN	≥ 80	≥ 20 kN	≥ 100
GRK 2	≥ 1.0 kN	≥ 100	≥ 30 kN	≥ 160
GRK 3	≥ 1.5 kN	≥ 150	≥ 35 kN	≥ 180
GRK 4	≥ 2.5 kN	≥ 250	≥ 45 kN	≥ 220
GRK 5	≥ 3.5 kN	≥ 350	≥ 50 kN	≥ 250

$F_{p,\,5\%}$ according to DIN EN ISO 12236
$m_{A,\,5\%}$ according to DIN EN ISO 9864
$F_{5\%}$ according to DIN EN ISO 10319

Table 8 Test fields and used geosynthetics

Test field	Section	Geosynthetic	Additional description
Field O	- 10 m to -2 m	Woven geosynthetic	GRK 3 Polypropylene
Field A	- 2 m to 7 m	without	-
Field B	7 m to 18 m	Woven geosynthetic	GRK 3 Polypropylene
Field C	18 m to 26 m	Non-woven geosynthetic	GRK 3 Polypropylene
Field I	26 m to 34 m	Geogrid	$R_{B,k,0}$ = 40 kN/m woven and welded
Field D	34 m to 46 m	Geogrid	$R_{B,k,0}$ = 30 kN/m grid laid and welded
Field E	46 m bis 58 m	Geogrid	$R_{B,k,0}$ = 20 kN/m punched and stretched
Field F	58 m to 69 m	Combined product Geogrid / Non-woven	$R_{B,k,0}$ = 40 kN/m laid and welded grid plus a layer of non-woven GRK 3
Field G	69 m to 78 m	Combined product Geogrid / Non-woven	$R_{B,k,0}$ = 20 kN/m punched and stretched grid plus a layer of non-woven GRK 3
Field O	78 m to 90 m	Woven geosynthetic	GRK 3 Polypropylene

$R_{B,k,0}$ as given by tensile tests DIN EN ISO 10319

In Field I, D and E three different types of geogrids were used. The examined types of geogrids can be characterized by the manufacturing methods "woven and welded", "grid laid and welded" and "punched and stretched". The tensile strength ranges between 20 kN/m and 40 kN/m. Combined products of a geogrid and a non-woven geosynthetic reinforce Field F and G.

Field A was constructed without a geosynthetic layer (unreinforced).

Geotextile robustness classes (GRK) characterize woven and non-woven geosynthetics. In addition to Table 7 the definition of the robustness classes (GRK) for geosynthetics according to the German standards TL Geok E-StB 05 and M Geok E are listed and give further information about the geosynthetics examined in the field tests.

4.4 Test results

The bearing behavior was checked first for a base course thickness of 30 cm. The results of static plate load tests are given in Figure 17. The maximum loading according to German DIN 18134 and ASTM D1194/1195/1196 is 500 kN/m², beneath the circular plate, of diameter 300 mm. The modulus E_{v1} (first loading) and E_{v2} (second loading) respectively are defined as secant stiffness between a stress of 150 kN/m² and 350 kN/m². After calculating the values of the E_{v1} and E_{v2} modulus, no significant differences of the different test fields were identified (see Figure 17).

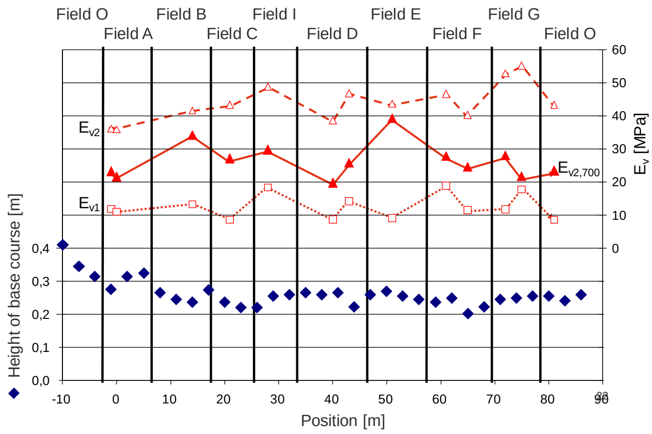

Figure 17 Thickness of base course layer (right side ordinate) and test results from static plate load tests E_{v1} and E_{v2} (left side ordinate) according to ASTM D1194/1195/1196 (German DIN 18134); modified static plate loading test up to 700 kPa mean stress evaluated by the modulus E_{v2},700

To increase the influence of the geosynthetic on the bearing resistance additional tests, in which the stress of the plate was further increased to 700 kN/m², was conducted. The values of the deformation modulus between zero stress and a stress of 700 kN/m² are defined by the parameter $E_{v2,700}$ in Figure 17. The values $E_{v2,700}$ were found to be between 20 MN/m² and 40 MN/m² and, combined with the E_{v1} and E_{v2} results, provide little indication of any influence of the geosynthetic layer for a comparably thin layer of the base course material as given by about 30 cm (see Figure 17). Even the unreinforced test Field A gives a deformation modulus E_v that is in the bandwidth of the results obtained in the fields that include geosynthetics.

For completion of the unpaved road, the thickness of the bearing layer was increased to 60 cm after the finishing of the first test phase. After about 2000 loaded truck passes, the rut depth was measured. Figure 18 gives the evaluation of the obtained values.

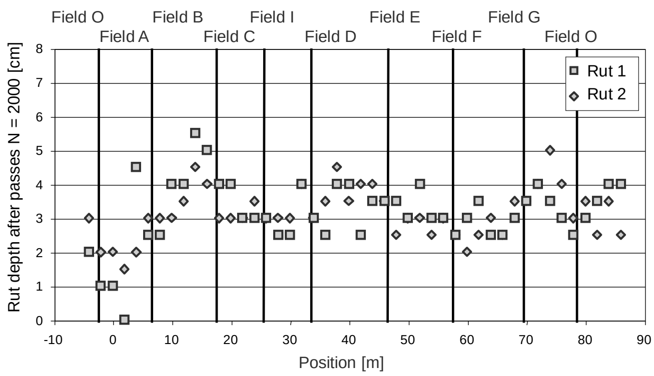

Figure 18 Rut depths after about 2000 passes of loaded trucks

The values of the rut depth measurements along the different test fields confirm the results from the previous test regime, depicted in Figure 17. The depths lie in between about 2 cm and 4 cm along the 100 m long test site and no clear influence of the geotextiles on the development of ruts can be seen.

The rather stiff subsoil compensates the bearing capacity improvement of the geosynthetic reinforcement, as identified in laboratory tests (see section 2 and 3). Also not measured during loading it seems that no significant strains emerge within the geosynthetics since the rut depths are same for rather soft non-woven geosynthetics (for example Field C) as well as for stiff geogrids and combined products of geogrid (Fields I, D and E) and non-woven geosynthetic (Flied F and G).

It should be noted that during the plate load tests on the 30 cm high base course, as well as during the actual loading from truck passes, little rainfall was measured, during a particularly dry summer. It is obvious that the low to medium plastic clay may lose strength and stiffness after water infiltration into the unpaved road. This loss of strength and stiffness of the subsoil will certainly be larger under the cyclic loading of the truck passes. It is expected that differences of the rut depths between the test fields will increase since the geosynthetics are expected to take a significant load through the membrane effect after the subsoil deforms gradually under traffic loads.

Along with the given boundary conditions for the above presented field tests where there was no visible effect of either increasing the modulus obtained by plate loading tests or decreasing rut depths, other aspects may govern the usage of geosynthetic layers, even by subsoils with higher bearing capacities. Especially for temporary roads the base course material should be separated from natural subsoil in order to reuse the costly gravel material, or even crushed material from hard rock. In some cases also for permanent unpaved roads, it is obligatory to ensure the protection of the natural soil and prevent the mixing of the base course material with the subsoil with time, under cyclic traffic loading.

5. DISCUSSION

The aim of the present study was to evaluate the effectiveness of geosynthetics in unpaved bearing layers with regard to the effects of different geosynthetics, different properties of the base course and for different subsoil conditions.

Within a research work, about 114 small scale and about 25 large-scale tests were carried out under static and cyclic loading following strict boundaries according to the soil installation and the loading conditions (Bräu and Vogt 2011). The carried out laboratory tests are in concordance with experiences gained in situ or from laboratory testing presented in other studies (Cardile et al. 2017, Christopher and Perkins 2008, Cuelho and Perkins 2009, Cuelho et al. 2014, Das and Omar 1994, Góngora and Palmeira 2016, Hsieh and Mao 2005, Latha and Somwanshi 2009, Nair and Latha 2014, Palmeira and Góngora 2016, Perkins et al. 2008, Suku et al. 2017, Tavakoli et al. 2017, Yadu and Tripathi 2013). The presented laboratory tests were verified by two field tests (Bräu and Vogt 2011) of which one is also presented briefly in this paper.

The effects of the strength and stiffness of the soft subsoil as well as of the geosynthetic layer was fundamentally examined by the use of model-scaled and large scaled loading tests carried out under controlled boundary conditions with regard to the subsoil condition, the compaction and the thickness of the base course. The results can be used to validate numerical models including simulations based on the method of finite elements. On the other hand, the limits of the effectiveness of geosynthetic layers could be only roughly analysed by the field tests due to the rather unfavourable boundary conditions.

Due to the extensive series of experiments, the increase in performance caused by the addition of an intermediate layer of geosynthetics was soundly assessed. Particularly, for comparatively low subsoil strength and low base course layer thickness, the use of geosynthetics was found to be very effective. Correspondingly, the use of a geosynthetic can reduce the thickness of the base course significantly. Under serviceability loading, settlements were also found to be significantly reduced.

The formation of permanent deformations under a cyclic load was reduced using geosynthetic liners in particular for a large number of load cycles compared to systems without a geosynthetic interlayer. However, the influence of the geosynthetics decreased steadily with increasing subsoil strength, e.g. in the conducted field test, where no increase in performance was observed for a dynamic deformation modulus of the subsoil between $E_{vd} = 10$ MN/m^2 and $E_{v2} = 15$ MN/m^2 and an undrained strength well above $s_u = 100$ kN/m^2. For these field conditions, and in the case of the base course thickness increased from about 25 cm (first test phase) to 45 cm and with a given loading of 2000 truck passes, there were hardly any differences in the development of ruts between systems with and without a geosynthetics including rather stiff geogrids observable.

In addition to these findings, the separation effect of geosynthetics for protecting the subsoil and a possible reduction of the load-bearing capacity of the subsoil because of rainfall, in particular induced by dynamic traffic loadings may increase the effectiveness of a geosynthetic layer strongly. Furthermore, a possible reuse of the base course material, which is decisive in particular for unpaved roads of temporary usage makes the use of geosynthetics necessary also for stiff subsoil conditions.

To evaluate the effectiveness of different geosynthetics it is necessary to evaluate the boundary conditions mainly given by the strength of the subsoil and the thickness of the bearing layer. Hence, a rather stiff geogrid may increase the useability of unpaved roads significantly in case of a weak subsoil and small bearing layer thickness. Furthermore, a product combining a geogrid and a non-woven geosynthetics seems show advantages if separation between a fine-grained subsoil and a coarse bearing layer is needed. In case of rather stiff subsoil conditions, including a sufficient undrained shear strength or a for whatever reason necessary high bearing layer thickness a layer of standard geosynthetics is a cost effective measure to both stabilize the grain skeleton of the coarse bearing layer material during compaction and to guarantee the separation between the subsoil and the coarse grained material.

6. CONCLUSION

Unpaved minor roads used for agricultural purposes and rural roads with low traffic volumes in general, as well as temporary access roads (especially for construction measures) usually consist of an unbound bearing layer of coarse-grained material. The results from the experiments both laboratory (small scaled and large scaled loading tests) and field tests show that the performance of the bearing layer can be improved by the use of geosynthetics. The effectiveness of the examined geosynthetics is strongly dependent on the strength of the subsoil and the thickness of the bearing layer. In the case of low subsoil strength and small bearing layer thickness, the effectiveness of geosynthetics is high. The thickness of the bearing layer, which often consists of rather costly, coarse grained materials sometimes even crushed materials from hard rocks, can thus be correspondingly reduced, which in particular can provide economic advantages - but also contributes to conservation of resources.

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