German Long-Term Experience with Reinforced Embankments on Soft Subsoil: Performance and Durability

D. Alexiew, Dr.-Ing., HUESKER Synthetic GmbH & Co.,
Gescher, Germany

K.-H. Blume, Dipl.-Ing., Federal Highway Research Institute,
Bergisch-Gladbach, Germany

ABSTRACT: Two projects of embankments on soft subsoil with high-strength basement reinforcement are shortly described. Started in 1981 and 1986, respectively they belong to the first one's using preloading plus reinforcement for autobahns and highways in Germany. Site conditions, construction stages, measurement data and evaluation are presented, including long-term reinforcement strain measurements until 1998. The geotextiles are still under tension. In 1995 high-tenacity polyester woven was exhumed from underneath the first embankment and analyzed for evaluation of durability. Important results are reported, confirming negligible loss of strength in 14 years. In conclusion, findings and recommendations for focal points of design, long-term reinforcement behavior and durability are summarized.

KEYWORDS: Embankments, Reinforcement, Long-term-measurements, Soft soils, Durability

1 INTRODUCTION

In Germany, in the construction of highways on soft saturated subsoils, increased use is being made of the preloading method. The advantages compared to soil replacement are not only the high cost savings but also countryside, environmental and ground water protection. The development of the preloading method is closely connected with the development of geosynthetics. The reinforcement function is of particular importance as it can be required not only to ensure the short-term stability during construction, but also the final long-term stability.

Since around 1970, the Federal Highway Research Institute (Bundesanstalt für Strassenwesen -BASt) has been involved in such projects on federal highways and autobahns. Investigation and measuring programs have been performed on large-scale 'test embankments'. The aim was to ascertain the behavior of the soft subsoil and the long-term behavior of high-strength geosynthetic reinforcement. Some of the experimental embankments were just loaded up to ground failure to verify the assumptions and results of the stability calculations.

For the Federal autobahn project BAB A 26, connecting the cities of Hamburg and Stade, a 'test embankment' was built near the town of Rübke (designated as 'Rübke-embankment' here) by the BASt in 1981, simulating a real autobahn-section on saturated peat with high-strength basement reinforcement. The project, materials used and deformation behavior until now are reported below.

Based on this experience the entire highway B 211 at the town of Grossenmeer was built in 1986 under similar conditions using a reinforcement of even higher strength (designated as 'Grossenmeer-embankment' here). The measurements in this case were extended by direct strain measurements on the high-strength woven used, which are continued up to now. The project, materials and most important measurement results including the long-term strains are shortly described.

In autumn 1995, after a 14-years-service period, parts of the high-tenacity polyester woven from underneath the 'Rübke-embankment' were exhumed. Tests and analyses were carried out for evaluation of durability. The most important findings are also presented.

2 TEST EMBANKMENT AT RUBKE

2.1 Description Of The Full-Scale Test

The dimensions of the embankment were in compliance with the standard cross section RQ 26 planned for the autobahn. Geometry and essential characteristic values of the peat subsoil are shown in Figure 1. The consolidation calculations resulted in a required preloading height of 3.6 m. A part of preloading had to be removed after consolidation. The stability calculations were performed according to DIN 4084 (Bishop's method) modified by reinforcement retaining force. Only low short- and long-term strains were allowed. The calculations resulted in a reinforcement mobilizing at least 90 kN/m at maximum 5% short-term strain, with an ultimate tensile strength (UTS) of at least 200 kN/m and ultimate strain < 10%. Only 1% creep strain in two years was allowed under 90 kN/m tension force. A high-strength polyester woven geotextile (Stabilenka® 200) was selected. The test comprises preloading with a subsequent consolidation period of just under two years, removal of preload, a reloading and the long-term measurements of the deformation behavior.

The 'test embankment' was constructed directly on the terrain without any soil replacement. First of all the woven was laid on the grass in July 1981.

Loads, heights and settlements to date are shown in Figure 2.

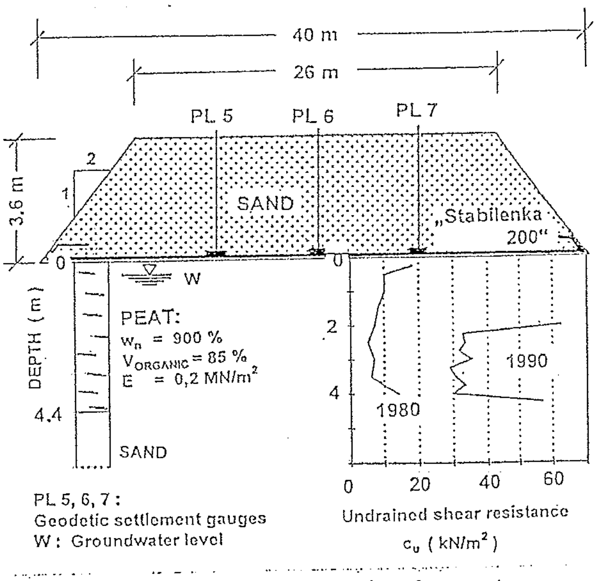

Figure 1. Full-scale 'test embankment' at Rübke (not to scale).

2.2 Course Of The Test And Measurement Results

Measurements of settlement, pore water pressure, base pressure, inclination and groundwater level were performed.

In this test, it was not possible to perform strain measurements directly on the fabric. Because, at this time, a measuring system with robust, precise and water-proof strain gauges was not available. Four years later, long-term resistant strain gauges were developed and applied for the 'Grossenmeer-embankment' (see section 3).

The development of the settlement shows a significant drop in the settlement rate, which was below 1 cm/year in the first year after the reloading. Nowadays the settlement rate is less than 0.5 cm/year with a decreasing tendency. Last measurements were performed in July 1998. The BASt is continuing the measurements.

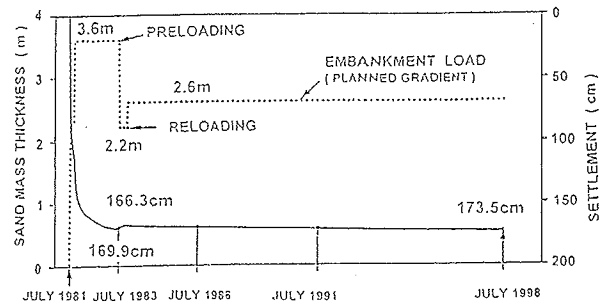

Figure 2. Load and settlement at Rübke from July 1981 until July 1998.

The high permeability of the peat in the unconsolidated state has made a rapid consolidation settlement possible.

For an embankment thickness of 2.3 m, the degree of consolidation was already 80% after two months. Very high primary settlements of around 1.1 m were measured. The transition primary / secondary settlements at a degree of consolidation of 90% occurred after 5.5 months. The maximum total settlement of the peat below the center of embankment mounted to around 1.6 m. The peat was compressed by around 40%.

The average strain of reinforcement derived from the settlement profiles (not shown) amounted up to 3%. Maxima and minima could not be registered due to absence of strain gauges (compare with section 3, 'Grossenmeer').

During filling and consolidation relatively low horizontal displacements in the peat occurred at the toe of embankment: maximum 18 cm in some depth and 12 cm on the ground surface. In a distance of 10 m from the toe of the embankment horizontal displacements of 1 cm to 3 cm were registered. The increase of undrained shear strength is shown in Figure 1.

2.3 Assessment Of The Measurement Results

The measurement results confirmed the feasibility of controlled construction of reinforced embankments on very weak subsoil (peat) by preloading, removing of preload and partial reloading to justify the final gradient. Due to the controlled preloading and the reinforcement, no failure-type deformations occurred, neither in the embankment nor in the foundation soil. The high-modulus geotextile (see section 2.1) allowed only small lateral spreading/squeezing deformations. Based only on the average strain the reinforcement looked understressed compared to design assumptions and calculations. But note, that strain (and tensile force) could had been higher e.g. in the usually critical zone (from the point of view of stability) under the slope and near the toe (see section 3.3). Summarizing: the simplified design calculations according to DIM 4084 agreed well enough for engineering purposes with the measured behavior. Nevertheless, continues measurements are an important tool to control the construction progress.

The measurement results and the collected experience even from July 1981 until March 1985 were adequate to recommend the preloading method with high-strength reinforcement for the entire new autobahn route BAB A 26.

2.4 Dynamic Loading Tests

Dynamic loading was performed on the large-scale test stand in the laboratory of the BASt and the 'test embankment' at Rübke . The aim was to investigate whether dynamic traffic loads influence the static settlement progress and cause additional secondary settlement.

In the laboratory, large samples from the peat (cylinder Ø 33 cm, sample height 45 cm) were statically loaded in accordance with the course of loading at the Rübke 'test embankment'. After final consolidation, sinusoidal stress pulses were additionally applied. The duration of the stress pulses was 0.25 s, the stress magnitude was 3.5 kN/m², and the interval between the stress pulses was 2 s. A track with a wheel load of 50 kN traveling at 80 km/h generates similar stress conditions at a depth of 2.5 m below the highway surface. 73,000 stress pulses were applied, and the settlement of the peat sample was measured continuously. The described dynamic cyclic loading of the large peat samples did not result in any discernible settlement.

For the purpose of a better evaluation of the laboratory results, dynamic loading tests were additionally performed on a paved part of the reinforced embankment at Rübke. Various traffic loads were simulated by different techniques, accompanied by measurements, and evaluated.

The results showed that no additional settlement of the peaty soil is to be expected as a result of traffic loads after primary consolidation. More information can be found in Blume and Hillmann, 1996.

3 HIGHWAY EMBANKMENT AT GROSSENMEER: TEST AND REFERENCE SECTIONS

3.1 Description Of The Project

Due to the positive results from the 'Rübke-embankment', the BASt recommended the preloading method with geotextile reinforcement for the construction of the new federal interstate highway B 211 at the town of Grossenmeer.

The BASt performed measurements on two sections of this project. The first one with steeper slopes, called here 'test embankment', had to be integrated later after reshaping in the standard highway embankment. The second one, called here 'reference section', was already from the beginning a standard highway embankment. The test program was extended here by direct short- and long-term strain measurements of the high-strength basement reinforcement.

The highway embankment at Grossenmeer has a length of around 2 km. The weak subsoil consists of layers of peat and organic silts in all 3 m to 5 m thick, underlayered by dense sand. According to pre-design calculations, typically an embankment thickness of 4.5 m was selected for the stage of consolidation (preloading). The consolidation period was expected to be about two years. After that layers of different adequate thickness had to be removed to fit the planned final gradient.

The following design soil parameters were assumed for the stability calculations according to DIN 4084 (see section 2.1):

Soft subsoil:	Undrained shear strength $c_u = 8$ kN/m²
	Unit weight $\gamma_n = 11$ to 13 kN/m³
Sand:	Angle of internal friction $\phi = 32.5°$
	Unit weight $\gamma_n = 18$ kN/m³

The calculation resulted in an allowable embankment height of only 2.6 m without reinforcement. To achieve the aimed preloading height of 4.5 m and the required FOS = 1.2 (global stability, temporary stage) according to DIN 4084, a reinforcement tensile force of about 200 kN/m was required (Blume 1995, Blume 1996). For reasons of deformation compatibility of compacted sand and reinforcement the corresponding short-term strain was limited to 5%, and the total strain (short-term plus creep) was not allowed to exceed 6% for several years. Based on the stress-strain and creep curves a high-tenacity polyester woven with an UTS = 400 kN/m and 10% ultimate strain was selected (Stabilenka® 400).

The earthwork for the entire 2 km-stretch was carried out from June 1986 until June 1987, followed by a consolidation period of 15 months. After then in some sections the embankment thickness had to be increased additionally from 4.5 m up to 6.5 m (including the 'reference section', see below) to compensate the unexpected high settlements. After a new consolidation period of 17 months, parts of the preloading thickness were removed in March 1990 for fitting the final gradient. The highway was opened to traffic in October 1990.

Since October 1990, after the end of the measurements directly accompanying construction, measurements have been and are being performed on the long-term deformation behavior of the subsoil, of the completed highway and on the strain behavior of the basal reinforcement.

3.2 Description Of The Tests

The main aim of both the 'test embankment' and the 'reference section' was to provoke the highest possible stress in the woven, selecting sections of the highway having particularly unfavorable subsoil conditions. Knowledge was to be gained of the long-term behavior of the reinforcement.

Under the 'test embankment', which was planned as a 'crash test', extremely high reinforcement stress had to be generated by rapid construction (4.5 m in four days), and by a steep slope of 1 V : 2 H. Nevertheless, ground failure had to be avoided because of the later integration in the standard highway embankment, after reshaping. Around 40 m away, in the 'reference section' with a standard (flatter) slope of 1 V : 3 H, the loading process lasted around a year.

For the direct geotextile strain measurements, the BASt developed a suitable strain measuring system which does not influence the strain of the fabric. Robustness, precision and water-resistance were proved in advance in contact with soil and under water also.

Settlements, pore water pressure, inclination and groundwater level of the subsoil were measured. The strain measurements were performed on, in total three cross sections, two of them in the 'test embankment' and one in the 'reference section'. In each case 9 strain gauges were installed at 2 m space. Additionally, settlement gauges were placed near the strain gauges (Figure 3 a, d).

3.3 Measurement Results And Assessment

The most important results are depicted in Figure 3 a, b, c for the 'test embankment' and in Figure 3 d, e, f for the 'reference section'. Note, that embankment material, single layer thickness, height (4.5 m) and reinforcement are the same.

The construction periods and slope inclinations are quite different, as mentioned above.

In Figure 3 b, c the graphs show the development only within the first 4 days (height from zero to 4.5 m). After that the increase in strain became less and, after 2 months, came almost to a halt (not shown). In the subsequent 25 months the strains asymptomatically came up to a maximum final strain of about 7% below the slope and 6% below the center of the embankment (not shown).

In Figure 3 e, f the graphs show the processes within around one year (height from zero to 4.5 m stepwise). The line with the number 1 corresponds to the 4th day (1.5 m sand), and with the numbers 2 to 5 to the 30th day after placing of the respective sand layer, at nearly constant time intervals.

Although the distance between the 'test embankment' and the 'reference section' is only around 40 m, the subsoil conditions seem to be considerably different, resulting in unexpected high settlements of the 'reference section'. In both cases a weak zone below the slopes was identified. Nevertheless, slope failure was not observed in the embankment body itself, neither for the 'test embankment', nor for the 'reference section'. On the contrary, the horizontal displacement of the subsoil near the toes became large, for the 'test embankment' up to 40 cm, destroying the inclinometer tubes. The ground tended to a 'squeezing-out', but a real failure did not occur. Note, that the typical subsoil-squeezing-mode cannot be checked by Bishop's method (DIN 4084) used for design calculations. Nowadays this mode should be checked e.g. according to Michalowski and Lei Shi (1993).

The reasons for the surprisingly high reinforcement-strains (and corresponding stresses) below the slopes in both cases are apparently both the weak zones and the squeezing-out tendency.

The strain increase and the horizontal deformations came to a halt shortly after completion of the construction. Based on the observation, it can be concluded that the reinforcement prevented both slope failure of the embankment and foundation soil failure due to squeezing of the soft layers.

The reinforcement strains exceeded at some locations the values of 5% (short-term) and 6% (long-term) assumed in design. The real mobilized tensile forces were higher than expected according to the stability calculations (DIN 4084, Bishop's method). The stress ratio (tensile force/ UTS) exceeded 50% clearly.

In 1993, the strain measurements in the 'test embankment' were terminated due to adjacent building activities. Only the results of the continued long-term measurements from the 'reference section' are reported below.

Note, that in Figure 3 d, e, f only the period from June 1987 to June 1988 is depicted. After that in Autumn 1988 the height of the 'reference section' was increased to 6.5 m to compensate the high settlements, and was reduced again just in Spring 1990 (Figure 4).

So far, at the center of the embankment, maximum strains between 6.8% and 7.6% and maximum settlements of the soft subsoil of between 190 cm and 205 cm have been measured. The strains presented in Figure 4 from commencement of construction in July 1986 until July 1998 remained practically unchanged after removal of the pre-loading height and opening of the highway to traffic in October 1990.

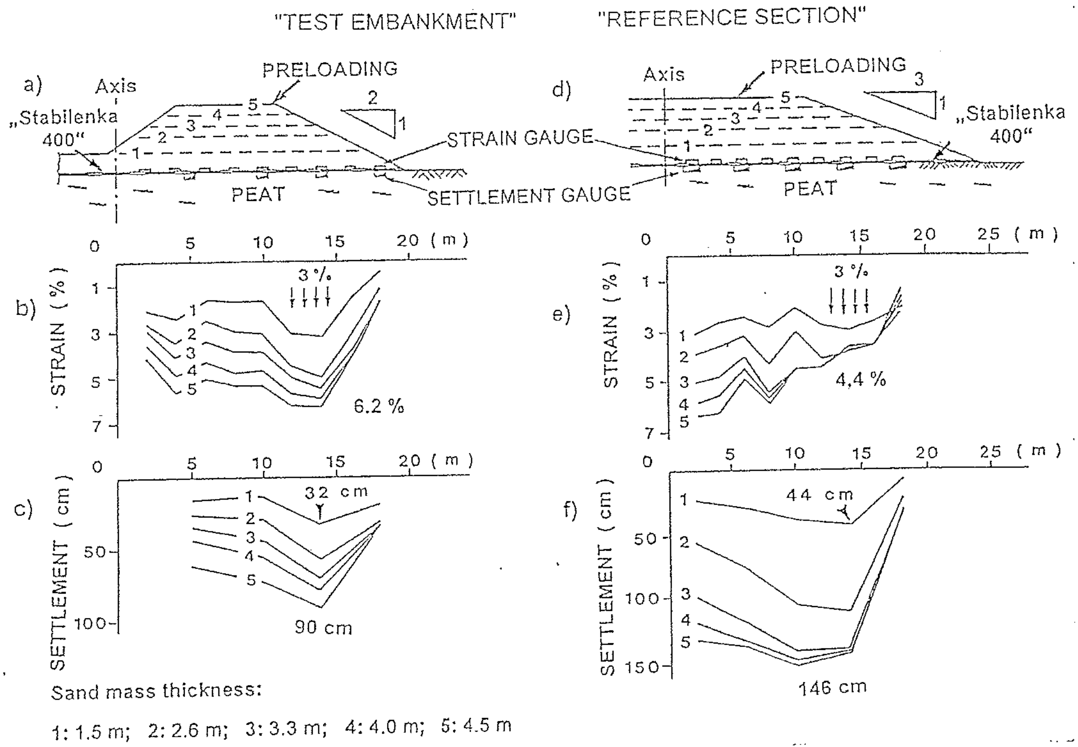

Figure 3. Grossenmeer: construction stages, settlements and strains

The constant strain level indicates that the reinforcement is still under tension after 12 years. It is difficult to evaluate the effective tensile forces from the registered strains with high precision now. In comparison with the short-term behavior a reduction in the effective tensile stress could be expected theoretically due to some factors. Relaxation could play a (negligible) role; for the high-tenacity polyester woven geotextile used, relaxation due to creep is very low due to general very low creep tendency. Furthermore, installation / compaction damage and environmental effects could have reduced the really the really available mobilized tensile force.

For the evaluation of relaxation the isochrones of the Stabilenka® 400 could be used, and the percentage of installation damage in sands is known in good confidence, being in the range of 5% to 10% for this geotextile. For evaluation of environmental effects the best way is to exhume and analyze an analogous reinforcement material, which has been embedded under similar conditions for a long time. For this purpose the Rübke-embankment offered a good possibility (see section 2).

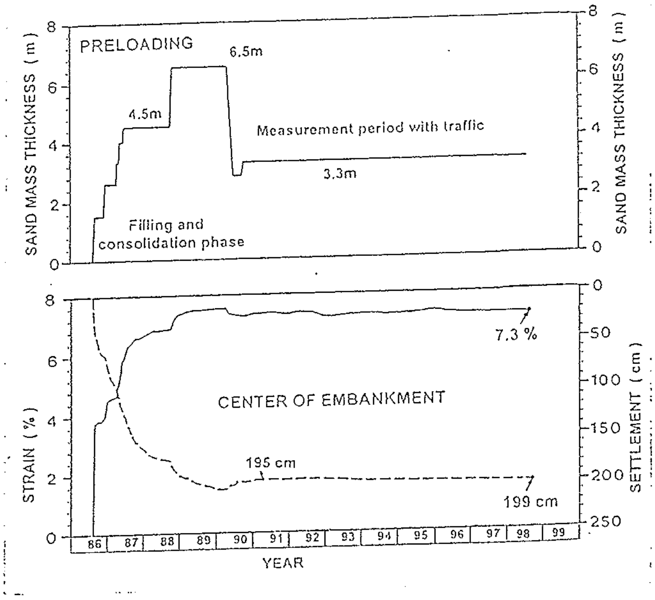

Figure 4. Variation of load, strain and settlement in the Grossenmeer 'reference section' (1986 to 1998).

4 INVESTIGATION OF A HIGH-STRENGTH POLYESTER WOVEN AFTER 14 YEARS EMBEDMENT IN SOIL

4.1 Description Of Exhumation And Tests

In 1995, the BASt initiated the investigation of exhumed of high-tenacity polyester woven samples. Since it is not possible to take samples from Grossenmeer, the BASt proposed, samples to be taken at Rübke (see section 2).

In September 1995, around 120 m^2 of the high-strength woven were exhumed from the embankment base after 14 years in use. The entire geotextile was lying below the terrain in the peat and groundwater due to settlements. By an excavator, embankment parts were removed down to the woven, from the slope to the center of embankment. At the beginning, it was possible to remove the remaining sand by hand (Figure 5). Due to the rapid rising of water, it was unavoidable to pull out and up most of the woven directly by the excavator. Thus, abrasion and damage of the fabric could not be fully avoided.

Figure 5. Rübke: exhumation of the high-strength woven (Stabilenka® 200) after 14 years

It was observed during uncovering, that the woven was still under tension before cutting. A considerable effort was necessary to lift up the edge of the woven by a shovel (Figure 6). This observation corresponds to the strains under the Grossenmeer 'reference section', which indicate considerable tensile forces until today also (Figure 4). Discoloration of the fabric due to contact with the rotted grass and the peat were clearly visible. In some places, grains of sand had penetrated its structure.

Samples for the testing institutes, participating in the investigations, were taken from four different geotextile areas after exhumation, corresponding to defined different positions in the base.

For each of the four areas the following tests were performed:

(1) Yarn tensile tests according to DIN 53834, T 1 with 15 individual tests per each area
(2) Analyses for determination of the carboxyl end groups (CEG) and of the molecular weights of the high-tenacity polyester
(3) Scanning electron microscopy (SEM) of filaments
(4) Chemical analysis of the groundwater (pH-values).

4.2 Evaluation Of The Results

The evaluation of the investigations regarding durability are almost completed. The most important results to date are presented here.
The results of yarn tensile tests form a better criterion for evaluation of strength loss due to environmental effects than the wide-width strip tests. Damage caused by installation, compaction and (in this case) removal and exhumation, and sand-grain inclusions in the woven structure has a less pronounced influence on the cleaned single yarn (although it can not be eliminated). The graphs in Figure 7 show the stress-strain behavior of the exhumed yarns. Each curve represents the average of 15 tests per area.

Figure 6. Rübke: the woven being still under tension after 14 years.

The specific yarn strength of the 'virgin' (brand new) high-tenacity polyester used (CEG < 27 meq/kg; number average molecular weight $M_n > 25000$; further exact data are known also) is shown in Figure 7, too. To perform a durability evaluation on the safer side, an increased possible average value of 'virgin' strength of 86 cN/tex (instead of 84.6 cN/tex) could be assumed. Thus, the residual strength is around 83% of the 'virgin' strength. The ultimate strain is practically unchanged. Note, that the yarn-strength loss of around 17% includes (in chronological order) the effects of weaving of the yarns producing the fabric, of installation and compaction damage, of biological and chemical degradation (chemical attack plus hydrolysis) and of exhumation process.

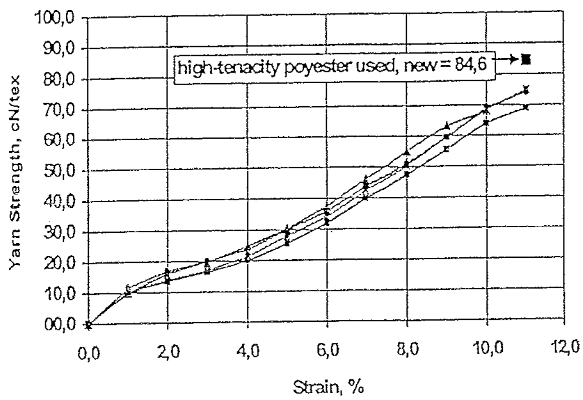

Figure 7. Specific yarn strength after 14 years in soil under groundwater level for the four different sampled areas according to DIN 53834, T 1.

The loss of yarn-strength due to the manufacturing process is 7% to 12%, on the average 9% (HUESKER Synthetic 1996). Further, for the Stabilenka® 200 mentioned loss of strength during compaction in sands of 5% to 10% has been observed. The loss of strength due to exhumation process is hardly to be identified exactly, but it can be set to 1% to 5% in this case. (Note, that a gentle exhumation was not possible, as mentioned above.)

The comparison of the percentage terms described above (weaving, compaction and exhumation) with the registered total loss of yarn-strength of about 17% results in 0% to 3% loss of strength due to environmental effects in this case.

Further, the SEM-photomicrographs performed indicate no chemical damage of the filament surface; it is completely smooth.

The comparison of molecular weights and number of CEG of 'virgin' and exhumed material leads to the conclusion, that 1% to 2% of strength-loss could be caused by changes in the polymer itself.

These latter evaluations of the microscopic and chemical investigations correspond well to the evaluation of loss in strength based on mechanical yarn-tests as mentioned earlier.

The pH-value of the groundwater is 6.6 on the average. This fact together with the SEM leads to the conclusion, that no chemical attack ('external' hydrolysis) has taken place.

The loss of strength of about 1.5% per 10 years, evaluated by different methods in this case, may be explained by 'internal' hydrolysis ('aging') in the groundwater and (unlikely) by biological effects (rotted grass, peat).

5 SUMMARY AND CONCLUSIONS

Two projects of embankments on soft subsoil with high-strength basement reinforcement have been started in Germany in 1981 ('Rübke') and 1986 ('Grossenmeer') respectively.

The 'Rübke-embankment' is a pure test-embankment for the autobahn BAB A 26. The 'Grossenmeer-embankment' is an integral part of the federal highway B 211. In both cases high-modulus polyester woven is used with 200 kN/m and 400 kN/m UTS, respectively, and 10% ultimate strain. For stability calculations DIN 4084 (Bishop's method) has been used, modified by reinforcement force. Measurement programs are performed up to now, including direct strain measurements at 'Grossenmeer'.

Woven from 'Rübke' was exhumed after 14 years under tension below groundwater to evaluate durability.

1. Stability calculations according to DIN 4084 are correct enough to prevent failure of embankment and/or subsoil, at least when high tensile force at low strain is mobilized to restrain deformations.
2. High-moduli for a long period (low creep) are important, because the reinforcement works after consolidation also. In the projects described it is still under tension after 16 and 12 years, respectively.
3. The high-strength reinforcement used proved to resist overstressing successfully for a long period.
4. Local weaker subsoil zones can easily result in reinforcement overstressing and/or failure tendency; it should be kept in mind when selecting safety factors.
5. Subsoil squeezing-out is recommended to be checked additionally to DIN 4084-calculations (Bishop) by other methods also.
6. The analyses of durability and operation conditions indicate in this case, that (internal) hydrolysis under stress in groundwater is the main reason for the registered loss of strength, which is negligible.
7. The loss of strength mentioned above due to 'aging' (environmental effects) is 1.5% to 2% in 14 years for the high-tenacity polyester woven used.

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