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# New shear creep tests on stitch-bonded GCLs: important results

H. ZANZINGER, LGA, Geosynthetic Institute, Nuremberg, Germany
N. ALEXIEW, HUESKER Synthetic GmbH & Co. KG, Gescher, Germany

ABSTRACT: A specially developed testing equipment and method for evaluation of the shear creep behaviour of GCLs with regard to the design of long term applications on slopes are described. The creep shear tests were conducted in a 30 cm × 30 cm shear device on two similar stitch-bonded materials with different internal shear strength. Individual tests with various constant shear stress ratios from 45% up to 90% related to the short-term shear strength were performed under defined vertical load for more than 1000 h. Until about 5000 h under 90% stress ratio creep displacements developed still slowly. In order to speed up the creep process the stress ratio was incrementally increased up to 110% for further 1900 h. Indeed, a state of accelerated creeping took place but still not a failure. An attempt to explain this phenomenon is made only theoretically, based on re-distribution of stresses. Analysis of the results obtained is shown considering allowed strains for in-situ conditions during the post-construction stage resulting in a method to forecast the allowed stress ratio for a defined design life. Finally the allowed stress ratios are given for the GCLs tested.

## 1 INTRODUCTION

The design of inclined multilayer soil-geosynthetic structures on slopes is controlled by the lowest shear resistance either in interfaces or in internal shear planes of the soils or geocomposites e.g. geosynthetic clay liners (GCLs). For long-term applications of GCLs it is important to consider the internal shear creep resistance, taking into account the time dependant internal shear creep process. Due to this the expected long-term shear resistance of a GCL can be lower than the short-term shear resistance and can control the design. Until now estimations of long-term shear resistance were simply made by modifying the internal shear resistance by additional reducing factors. A better solution is to estimate the allowed long-term shear resistance by direct shear creep tests so far as possible. The paper describes briefly some basics and earlier activities of the authors as background for the recent research with another GCL. The main results of the current examinations are presented and compared to the previous one; the paper focuses on the allowed long-term shear stress-ratio of the new GCL tested, which is evaluated from the point of view of the allowed shear displacement, and not only with respect to failure.

## 2 INTERNAL SHORT-TERM SHEAR STRENGTH

### 2.1 *Overview of problems*

The internal shear strength or resistance of a GCL is the maximum shear stress, which the GCL can bear within its plane, i.e. in the plane between the confining geosynthetics. Its value depends on many factors including time, which is always a factor when dealing with geosynthetics. This internal resistance is among others a key-issue in sliding stability calculations. Further explanations can be found in (Zanzinger & Alexiew 2000).

The hydrated bentonite alone provides a very low shear strength; the angle of internal friction amounts only to $\varphi = 5°$ to 7°. Hence, the internal shear strength of GCLs depends mainly on the entire synthetic internal structure of the product: yarns and fibres and their connection to the confining geotextiles on both sides of the encapsulated bentonite, and from these geotextiles as well. In this synthetic system creep is of great importance. Nevertheless, in most cases only the short-term internal shear resistance is being tested by direct short-term shear tests; after that the long-term value is usually evaluated on the base of analyses of the possible long-term behaviour of the polymeric elements. This procedure is strictly speaking questionable.

However, short-term resistance is the base for comparison and later to relate to long-term behaviour; thus, the short-term testing is a must.

### 2.2 *GCLs tested*

Two similar stitch-bonded GCLs with similar structure were tested, both stitched by HDPE monofilament yarn, diameter ∅ = 250 µm, but with different spaces between the stitch lines. Initially the GCL with narrow spaced stitches was extensively examined in order to prove generally the practicability of the shear-creep testing procedure developed (Zanzinger & Alexiew 2000). Based on the insight from this first test series further shear-creep tests were performed on a new GCL (NaBento® RL-N) with enlarged stitch spaces. Basically the second test series will be presented herein; the first tests will be only summarised briefly.

### 2.3 *Determination of the internal short-term shear strength*

Figure 1 shows the shear-box test device (30 cm x 30 cm) used to test the short-term shear strength of both GCLs before the shear creep tests. The tests are displacement-controlled; shearing process is carried out at constant shear rate of 10 mm/h and a constant normal stress of 20 kPa on completely hydrated samples. Both the upper and lower side of the sample are fixed by special nail plates with 2 mm long, finely distributed nails (1 nail per cm2). In this way an equal shear stress transmission over the total sample area is ensured. The position of the nail plates is adjusted in such a way, that the nails of the two plates do not influence the shear process. Additional load cells in the lower shear box control the transfer of the vertical load to the sample.

In course of the test shear forces continually increase until they reach a maximum and then fall down to a residual shear force. A typical curve of the GCL actually examined is shown in

Figure 1. Schematic diagram of test equipment for testing internal shear strength of GCLs.

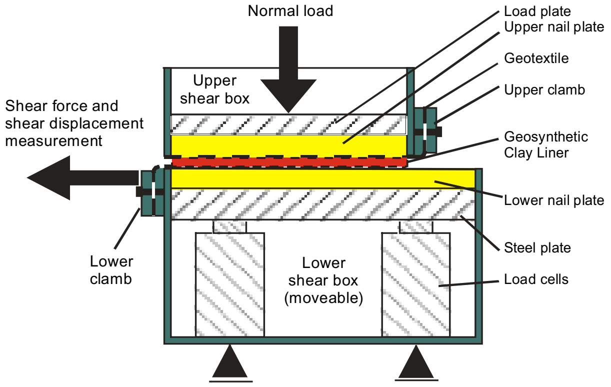


Figure 2. Typical shear displacement vs. shear stress diagram of the new GCL tested.

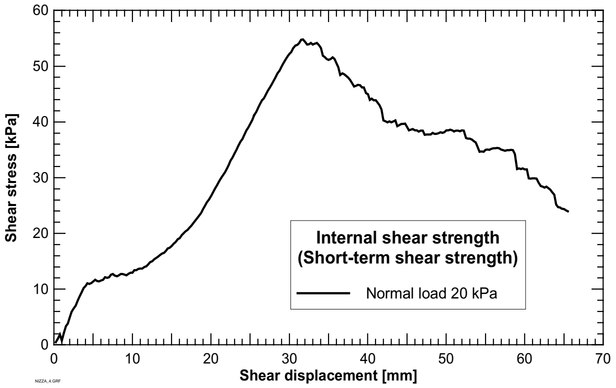


Figure 2; the shear strength of 54.8 kPa is used later herein for comparisons with the long-term shear behaviour (stress ratio, see below).

In the previous test series the typical value was 67.6 kPa short-term shear strength at approx. 30 mm shear displacement.

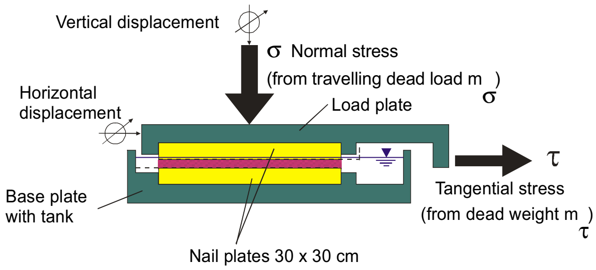
## 3 PRINCIPLES OF THE SHEAR CREEP TEST

The behaviour of a GCLs fibres or yarns under long-term shear stress is comparable with the tensile creep behaviour of synthetic reinforcing materials. However, the failure process is made up of several specific failure mechanisms. All GCLs have the following in common: the failure can occur in yarns/fibres that hold the geocomposite together and/or in the junction points to the confining (encapsulating) geotextiles. Additionally the failure is influenced by the mechanical behaviour and the stress level of each individual yarn or fibre being under load. An equal load distribution among all these components can hardly be assumed. Consequently, a pure mathematical evaluation of the long-term shear strength of GCLs by reduction factors is difficult and questionable; these theoretical results seem to be not sure enough. Moreover, the influences of different factors may change under long-term shear stress compared with short-term tests.

Thus, the best way is to perform directly long-term shear tests.

The shear creep tests are load-controlled tests similarly to the well known tensile creep tests on geosynthetic reinforcements. The principle with GCLs is to evaluate the time dependent shear deformations corresponding to different shear stresses and finally the shear failure (if it can be reached during a test). An important term is the so called shear stress-ratio. It is the relation of shear stress actually applied in a test to the ultimate shear strength from the short-term tests. In the test the GCL is subjected to a certain constant vertical stress and to the particular shear stress-ratio for a long-term period. In the course of the test, the shear displacements are measured continuously. The result is the time-dependent shear behaviour, which can be displayed in a graph. A more detailed picture of the core of the testing device is given in Figure 3.

Figure 3. Details of shear-creep device and test.



Some specific important issues are: the normal stress is applied by dead loads allowing for long-term precision and constancy especially for the important low loads simulating 1.0 m to 1.5 m of soil, any combination of normal and shear stresses can be simulated (Trauger et al. 1996) etc.

Depending on the stress-ratio applied, shear creep is low, high or there may even be a failure within the period of the test (Koerner et al. 1996). The process has three stages: initial, steady and progressive creep ending in a failure.

The steady stage takes a long time for low shear stress-ratios, so that the failure can occur only after an extremely long period. This probably applies to the EPA test sites in Cincinnati (Carson et al. 1998) and to long-term tests on tilting plates (Heerten et al. 1995). For this reason it is important to have the possibility to apply high stress-ratios, which induce the shear creep failure in an acceptable time or allow for a realistic displacement-based evaluation of allowed stress. The experience from the tested GCLs shows that this is not always simply to be realised even with the device used, which ensures really high shear stress-ratios (see below).

## 4 SHEAR CREEP TESTS PERFORMED

### 4.1 *Test procedure*

In the previous test series, medium high 5 stress ratios (45% to 65% related to 67.6 kPa) were applied separately on different samples for more than 1000 h, but the phase of accelerated creep could not be reached.

Therefore, in the new tests separate high stress ratios starting from 65% up to 90% (related to 54.8 kPa) were chosen from the same beginning. A total of 5 trials were carried out on different samples, but all they being cut from the same longitudinal strip of GCL to minimise scattering of results. Each dry sample was installed in the test device and was subjected to 20 kPa normal load immediately after adding of water, and then loaded practically simultaneously by a tangential stress corresponding to the chosen particular stress ratio. Immediate shear displacements occurred within 1 to 2 minutes after shear stress was applied. From this (time) point on, the increase of shear displacements, or creep rate slowed down considerably; the material entered the phase of steady creep. Measurements of swell heaving indicated almost finished hydration phase within approximately 2 days. Over the total period of testing the specimens remained stored in deionised water, settlements and shear displacements were registered continuously. The trials with stress ratios up to 80% were monitored over about 1800 h, the test with the highest stress ratio 90% continued about 5000 h.

### 4.2 *Test results*

The results for the first test series with the "old" GCL are summarised in Figures 4 and 5 (modified from Zanzinger & Alexiew 2000). The records for the tests with low stress ratios from 45% up to 65% are depicted in Figure 4. In Figure 5 additional test results are displayed showing the shear creep progress of one specimen under stepped increase of shear stresses. The material behaviour corresponds to common engineering sense and confirms the practicability of the testing device and technology applied, presenting a typical creep behaviour under such stepped loading procedures.

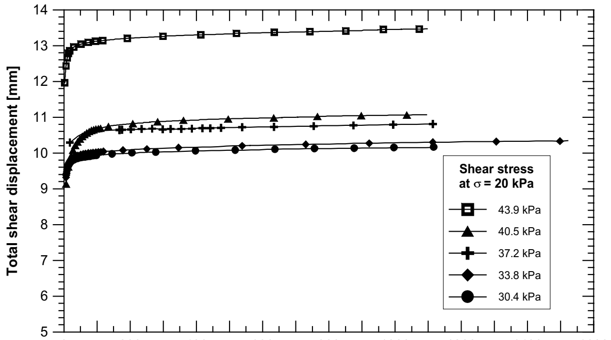


Figure 4. Shear creep of the "old" GCL for stress-ratios of 45 to 65%.

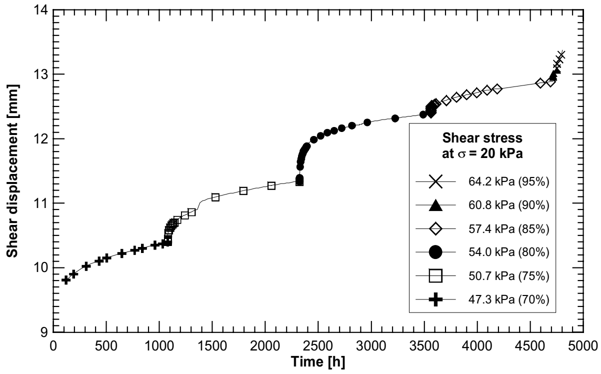


Figure 5. Shear creep of the "old" GCL for stepped increased stress-ratios of up to 95%

Now the results for the "new" GCL are presented starting with significantly high stress ratios. Figure 6 comprises the results for the three most relevant highest shear loads in a linear scale, and Figure 7 in a log-time scale. The three curves correspond from bottom to top to 70%, 80% and 90% shear stress ratio. The tests for 70% and 80% stress ratios were interrupted to save testing time, because they were clearly far away from any limit state of displacement or failure. Because until nearly 5000 h no signs of creep rupture or increase of creep rate were registered in the test with 90% stress ratio, it was decided to try to approach the limits. Thus a stepped increase of shear stress ratio was applied as shown in the graph; compare e.g. the analogous procedure in Figure 5. For the stress ratios from 92% to 110% applied over 1900 h until the 6700 h no shear failure occurred, but an increasing creep displacement can be identified. The surprising fact, that shear stresses in the last testing phase (dotted line in the upper curve in Figure 7) exceed the short-term shear strength without failure might probably be explained by stress redistribution. Long-term loading beneath the peak shear strength leads to redistribution and equalising of the stresses under the bonding yarns, thus allowing transmission of higher shear stresses. In a short-term shear test the stress impact causes probably an "immediate" rupture of the "activated" (fully loaded) bonding connections afterwards the rest that has been only partially loaded fails. This behaviour might be only explained by the different connection strength of the numerous of particular yarns. Comparative short-term shear tests executed with different shear rates are necessary to check that assumption.

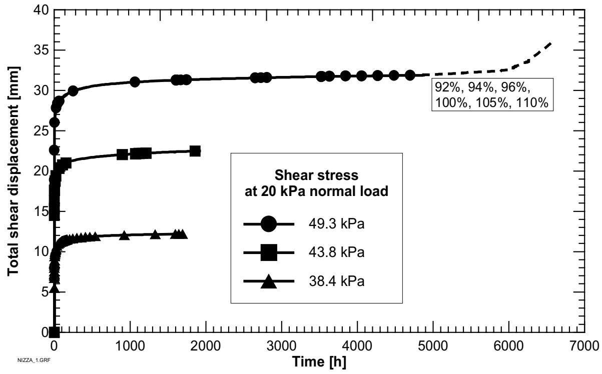


Figure 6. Shear creep of the "new" GCL for high stress-ratios of 70% to 90% and more: linear time scale.

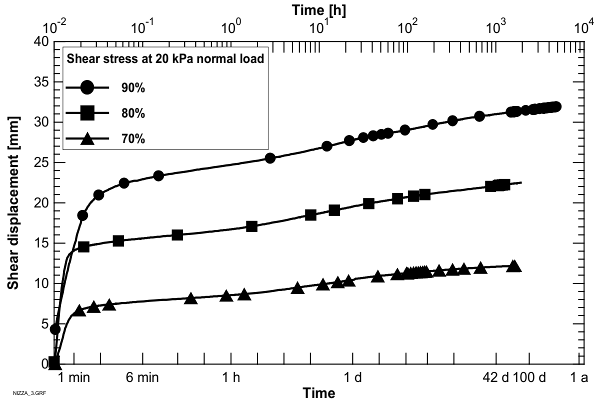


Figure 7. Shear creep of the "new" GCL for high stress-ratios of 70% to 90%: log time scale.

### 4.3 *Prediction of the allowed long-term shear stresses*

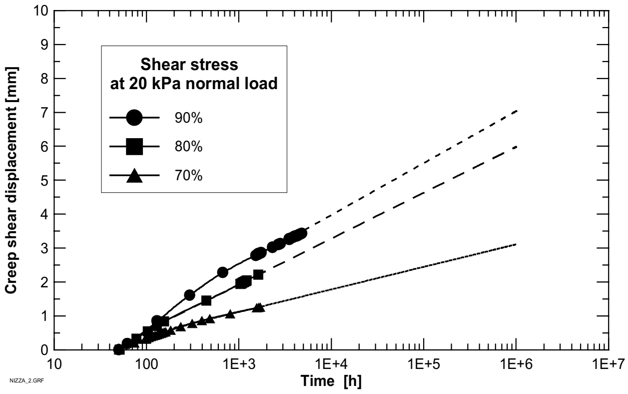
For stability calculations finally an allowed value of shear stress ratio should be obtained. For this purpose two different criteria may be used: the shear displacement and the shear failure. Because it was not possible to provoke a shear failure in the test in an acceptable time even for shear stress ratios higher than 100% (higher than the short-term shear strength), we will focus on the shear displacements.

From the point of view of engineering applications on steep slopes shear displacements in the first hours and days are not from real interest, because during that time the soil cover above the GCL is still under construction and consequently any deformations in the range of millimetres are being compensated permanently. Moreover, during this construction stage the GCL is being stochastically overloaded by earth moving equipment. Consequently the relevant criterion is the shear displacement after construction: between the end of construction stage and the end of the so-called design life, because deformations in the ready built system could have critical consequences. Depending on the structure, the design life could be 30, 70, 100 years or more. The construction period of a cover system could be assumed to be at least 2 days or more for the entire slope, on which the GCL is installed. For the further analysis the end of construction and start of use of the structure is assumed to be 50 h. This is an assumption on the safer side compared with e. g. 100 h or 200 h, simply because the shorter the construction time the longer the time for creep until the end of design life.

For the purpose of this analysis the graphs displayed in Figure 7 were modified and shifted: the three curves were shifted to the point at 50 h, serving now as a new origin of coordinates (Fig. 8). With this transformation it becomes possible to analyse the post construction stage in a precise way. For design purposes the engineer has to know the allowed shear stress ratio for the design life foreseen. Generally, for a creep process, the higher the stress ratio the shorter the time allowed. In order to evaluate the stress ratios and corresponding times allowed, based on the displacement criterion applied in this analysis, an acceptable limitation of (critical) shear displacement has to be defined.

It can be shown that shear displacements of the GCL up to 10 mm would not generate critical strains in a top soil layer for slope lengths of 2 m or more. Thus 10 mm are set as limiting value in Figure 8. The extrapolation of the graphs e.g. up to $10^6$ hours (Fig.8) results in about 7.0 mm shear displacement between end of construction and 114 years ($10^6$ h) for a shear stress ratio of 90 % (49.3 kPa shear stress). The safety margins, respectively resources in terms of shear displacement amount to: (10 mm – 7 mm) / 7 mm = 40%. The GCL is clearly far below the defined limit state of serviceability.

Figure 8. Shear creep of the tested “new” GCL at high stress ratios after end of construction.



The same conclusion could be made regarding the ultimate limit state: note that these more precise analysis presented based on displacement criterion confirms the first rupture related conclusions based on Figure 6. The graphs (Fig. 8) could be extrapolated to longer times than $10^6$ hours but the confidence of extrapolation will decrease. Summarising: for design purposes the allowed shear stress ratio can be set to at least 90% for at least 114 years.

## 5 FINAL REMARKS

About two years ago shear creep tests were performed on a stitch-bonded GCL using an especially developed testing device. At that time the allowable shear stress ratio was definitely underestimated; the applied stress ratios were mostly too low. Nevertheless the tests were important and useful providing first values for the long-term shear strength of the GCL tested and helping to refine test procedures.

Recently new test series were carried out with new stitch-bonded GCL. From the same beginning high shear stress ratios of up to 90% for a longer time (5000 h) and up to 110% (for about 500 h) were applied without failure. Due to the high resistance to shear failure post construction displacement criteria were used to evaluate the allowable stress ratio. Such a procedure was applied for the first time herein.

All results seem to be plausible and can be used for design purposes.

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