Prediction of long term shear strength of geosynthetic clay liners with shear creep tests

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ABSTRACT: Geosynthetic Clay Liners (GCL) are widely used as components in cover systems of landfills. Especially on slopes the internal shear strength is very important. The short term internal shear strength is easy to determine compared with the long term internal shear strength. Shear creep rupture tests with a specially developed equipment were conducted to predict the failure of GCLs under constant shear load at a defined normal load. A logarithmic function is used to verify the measured data. With shear creep tests on a stitch-bonded GCL a procedure to determine the long-term shear strength of GCLs is proposed.

1 INTRODUCTION

Geosynthetic clay liners (GCL) are being used more and more often recently for long-term applications on slopes, e.g. on landfill cap seals. It is necessary to know the long-term internal shear strength of the GCL as well as the shear strength in the contact planes of the layer construction. This can prevent a rupture of the total slope construction in the long term as a result of an internal failure of the GCL.

The bentonite layer in the geocomposite GCL has a very low shear strength, a friction angle $\varphi = 5$ to 7° of the hydrated bentonite. Accordingly, depending on the type of GCL, the internal shear strength is increased by stitching (form-closed), needling (tensional) or by gluing (adhesive). The behaviour of the GCL under long-lasting tangential loading depends on the material and the type of strengthening, on its creep tendency and on the long-term resistance of the fibres and yarns used.

Previously, the internal long-term shear strength was estimated from the results of short-term shear box tests or tilting plate tests, together with reduction factors. With our present state of know-ledge, it is possible to make a sound, reliable forecast on the long-term permissible shear loading of the GCL using shear creep tests. The principle, its method of implementation and the evaluation of shear creep tests are described here, taking a stitch-bonded GCL as an example.

2 INTERNAL SHORT-TERM SHEAR STRENGTH OF GCL

The internal shear strength of a GCL is understood as being the maximum shear stress which the GCL can show within its plane, under even loading with a defined normal stress in the conventional direct shear-box test.

The shear strength of mechanically bonded (stitched or needled) GCLs is largely determined by the synthetic elements which ensure the composite construction of the GCL components. In the case of needle punched GCLs, these are fibres which extend through the bentonite layer and are anchored in the outer geotextiles. In the case of the stitch-bonded GCL examined, this is an HDPE mono-filament yarn, diameter ∅ = 250 µm, with which the outer geotextiles and the internal bentonite layer and supporting nonwoven material are stitched together.

It is clear that in both cases the shear strength of the GCL is dependent on the strength of the fibres and yarns, the number of load-bearing joints and the strength of the connection/anchorage with the outer geotextiles. It is known that synthetics have lower long-term strength compared with short-term strength. So where the mechanical behaviour of GCLs under shear loading is concerned, one should distinguish between short-term shear behaviour and long-term shear behaviour and take these into consideration in dimensioning constructions. It is also more correct to refer to the internal shear strength of the GCL determined in the shear-box test as the short-term shear strength.

Shear boxes sized 30 x 30 cm are generally used to test the internal shear strength of GCLs. The GCL is subjected to a constant normal stress. The tangential stresses are created by shearing the geotextile layers of the GCL against each other at a constant speed (generally 10 mm/h).

The fixing of the GCL in the shear box is very important, so that the tangential stresses are transferred over the total area, both in the upper and lower side of the GCL. One effective method is using special nail plates moulded in epoxy resin, with 2 mm short, finely distributed nails (1 nail per cm^2). The nail plates are placed on both sides of the GCL. The nails of the two nail plates may not touch each other at any time. The GCLs are completely hydrated before shearing (a swelling period of 48 h is generally sufficient), in order to test them in their least favourable condition). The hydration of the GCLs is carried out at the appropriate normal stress. It is considered sufficient to conduct short-term shear tests in "wet" state rather than "under water" as the tests conducted in both the conditions gave identical values.

Figure 1 shows the test equipment used to test the internal shear strength of GCLs. The tests are path controlled, i.e. the shearing process is carried out at a constant speed, with the shear forces continually increasing until they have reached a maximum. The shearing process should be carried out until reduced to a constant residual shear force. Assessment of the measurements may be made in the classical manner in accordance with Mohr-Coulomb. Figure 2 shows a typical shear stress shear path diagram for the stitch-bonded GCL examined.

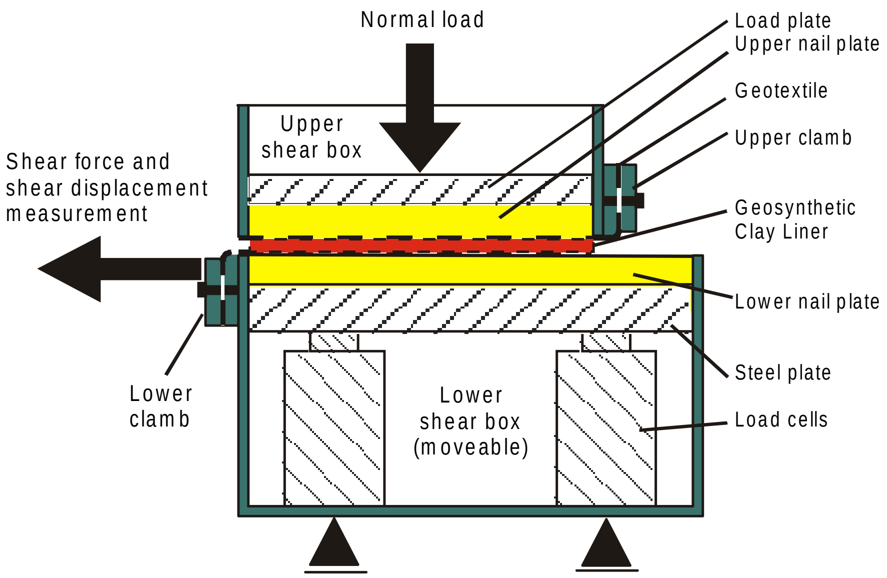

Figure 1. Schematic diagram of test equipment for internal shear strength of GCLs.

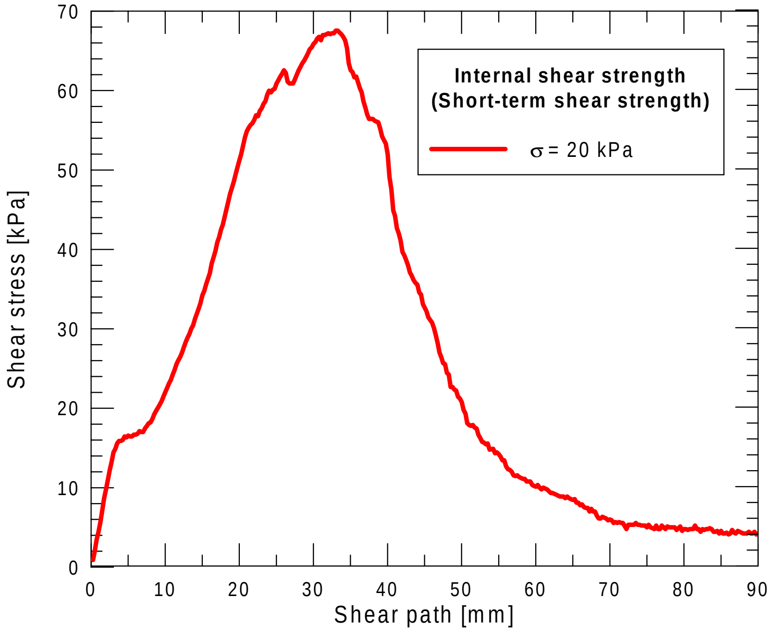

Figure 2. Typical shear stress/shear path diagram of a stitch-bonded GCL.

3 SHEAR CREEP BEHAVIOUR OF GCLS AND PRINCIPLE OF THE SHEAR CREEP TEST

Establishing the long-term shear strength proves to be considerably more difficult. Here there are no standardised test constructions. Research is being carried out on this at various locations. Carson et al. (1998) report on test sites to examine the long-term shear behaviour of GCLs on slopes in typical American landfill cap seals. These EPA test sites were set up in Cincinnati in November, 1994. As before, any shear deformations are measured in all the test sites. It is assumed that these are creep deformations and accordingly the sites are to be kept under observation for some more years with measurements being monitored.

There are various ways and means of examining shear creep behaviour in the laboratory. Heerten et al. (1995) report on test constructions on inclined planes. These tried to re-create the situation on the spot. The problem is that the bentonite must constantly be kept moist with a permanent flow of water over the GCL, making long-term tests very complicated. Moreover, it is very difficult to ensure long-term centric transfer of forces via staggered dead loads on the system. The critical disadvantage of such tests is, however, that the safety interval is not recognisable or not ascertainable.

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 failure mechanisms. For example, in the case of needle punched GCLs, there is a process of unlooping, which is further influenced by the fibres rubbing together. The decisive failure process with all GCLs is the tearing of the fibres or yarns that hold the geocomposite together. Failure is also dependent on the strength of the geotextiles in which the fibres are anchored. The number of fibres is formulated in mathematical proofs. It should be remembered that the carrying capacity of the fibres is largely dependent on how deeply they are anchored in the geotextile, how strongly pronounced the orientation of the fibres is and how tightly each individual fibre is fixed. Accordingly, one may assume that only a certain percentage of the fibres transmit the shearing force, while the rest can never take up any load, or if so, only after the failure of the load-bearing fibres.

Under these conditions, mathematical proofs of the long-term shear strength of GCLs reducing the short-term tensile strength of the fibres by reduction factors are very difficult and questionable, as the standards for comparison are fraught with considerable scatter and errors. Moreover, the influences of different factors may change under long-term shear stress, compared with short-term tests.

It is better to test the GCL in load-controlled shear creep tests. The shear creep tests are planned similarly to the familiar tensile creep tests on geosynthetic reinforcements. Under a constant normal stress, the GCL is subjected to different shear stresses over a long-term period, with these, related to the internal short-term shear strength, being termed shear loading rates. In the course of the test, the shearing deformations are measured, their chronological course giving the shear creep behaviour of the GCL. Depending on the rate of stress selected, or the tangential stress used, shear creep is low, high or there may even be a failure within the period of the test (Koerner et al.,1996).

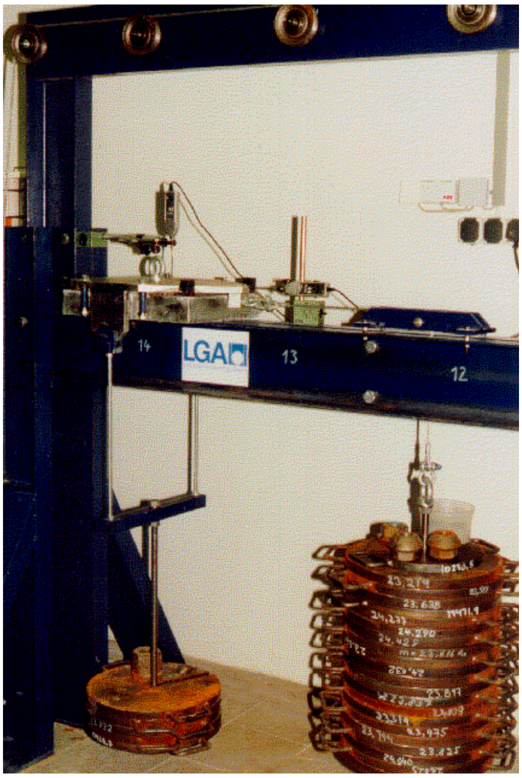

Figure 3. Shear creep test equipment.

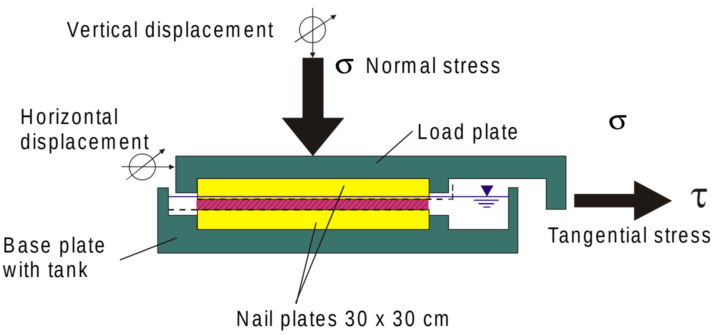

Figure 4. Schematic diagram of test equipment for testing the shear creep behaviour of GCLs.

The samples are also held in the test rig by nail plates in a tank filled with water (Figures 3 and 4). This method lets tests be carried out with practically any loading rate to simulate applications in a wide range of constructions (Trauger et al., 1996). Dead weights are sufficient for small loads, while hydraulic jacks must be used for large loads. Any shear stress is possible at the same time. By selecting the standard and tangential stress pairs, any situation relevant to practice can be re-created.

Creep rupture behaviour or also creep failure is a phenomenon of all visco-elastic materials. It is a time-dependent effect under stress conditions below the short-term strength. After application of a constant load below the tensile strength, the fibre begins to stretch; it creeps until the limit of stretch has been reached and then it tears. This chronological process accelerates as the load becomes greater, i.e. the greater the loading rate of the fibre. This is the (relatively) simple process with tensile creep loading. With the shear creep loading of a geocomposite, even with a mineral component such as the GCL, the processes are more complicated.

Here, while the fibres and yarns largely accept the transmission of shearing force, a certain proportion of the shearing force, although small, is also transmitted through the bentonite. Moreover, the fibres and yarns observed here are not aligned in the direction of tensile loading, as with reinforcing products, but are more or less vertical to the tangential loading. It is only in the course of the tangential loading that the fibres and yarns are orientated in the direction of loading, thus becoming subject to tensile stress.

Basically and finally, however, the typical sequence occurs under shear creep loading as in Figure 5, similarly to tensile creep tests.

Shear creep behaviour is characterised by time-dependent shear deformation under constant shear loading. Three stages may be recognised, a non-linear initial stage, the linear stage of stationary creep and an accelerated creep at incipient failure.

The creep behaviour of a GCL is not very expressive of the total “creep rupture behaviour” of the GCL as long as it is in the linear phase, i.e. the stationary creep phase, because shear creep failure has not yet been reached. This stage takes a long time for low levels of shear stress, so that the failure point occurs very late. This probably applies to the EPA test sites in Cincinnati and to long-term tests on tilting plates. For this reason, time-lapse tests which induce the shear creep failure more quickly must be carried out. One possibility would be to carry out tests at higher temperatures. This system cannot be applied here because of the condition of the bentonite.

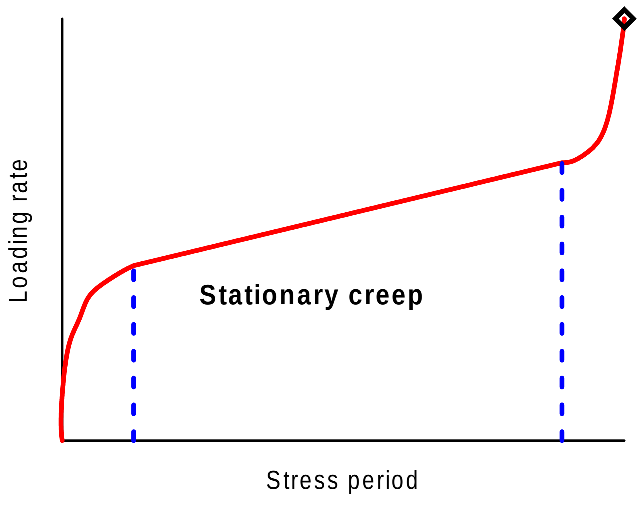

Figure 5. Diagram showing time-dependent internal shear behaviour of GCLs.

The remaining possibility is to carry out tests at high loading rates. At very high loading rates, shear failure occurs in a relatively short time. By applying the loading rates over the failure times on a logarithmic scale it is thus possible to determine the point of failure for low loading rates by extrapolation.

Put simply, at a pre-determined tangential stress, the point may be calculated after which this can no longer be accepted by the GCL. Experience shows that the internal shear strength of a GCL is not a constant figure, but depends on the loading rate. The above statement is therefore valid in each case in combination with a normal stress (loading rate) applied to the GCL.

To summarise, shear creep tests of the type described here (Figure 4) are advantageous for four main reasons:

(a) Any σ/τ combinations are possible; a wide range of construction situations can thus be recorded.
(b) A safety interval to the shear creep failure is unambiguously definable.
(c) As with all tests of the “black box” type, we are not concerned with hypothetical internal mechanisms, but a clear, safe result is achieved.
(d) The tests may be reproduced precisely.

4 SHEAR CREEP TESTS ON A STITCH-BONDED GCL

In this case, shear creep tests with a stitch-bonded GCL (trade name NaBento®) are presented. A total of 11 individual tests were carried out at 11 different tangential stresses, with a normal stress of 20 kPa in each case. These tests were, as a rule, observed and measured for more than 1,000 hours. All samples were stored permanently in de-ionised water over the total period of testing. Direct shear box tests were initially carried out at a normal stress of 20 kPa to obtain the internal long-term shear strength. In the case of the batch tested this was 67.6 kPa, with a failure shear deformation of app. 30 mm.

In the first series of tests, five new samples were installed in a dry condition. Immediately after adding water, they were subjected to a normal stress of 20 kPa and, practically simultaneously with a tangential stress of 30.4 kPa. This corresponds to a loading rate of 45% with the first shear creep test.

Within the first 24 hours, the GCL was almost completely hydrated, as could be seen from an increase of approx. 2 mm in thickness. The shear deformations achieved approx. 7 mm immediately after application of the tangential stress and then increased to approx. 9.5 mm within the first 24 hours. Approximately from this point, the increase in shear deformation, or better the creep rate, slowed down considerably.

The stage of so-called stationary creep has been reached. This first test in the first series of tests represents the following four tests, which were carried out with loading rates of 50%, 55%, 60% and 65%. In all cases, the increases in thickness or swellings progressed evenly. The initial shear deformations varied between 6 and 10 mm and as a rule, stationary creep had set in after 24 hours.

All absolute shear deformations from test series 1 have been plotted against time in Figure 6. It can clearly be seen that the shear deformations in the non-linear initial stage increase considerably until they proceed to the linear phase of stationary creep after approx. 1 day. There was no trace of any transition to accelerated creep here.

With a second test series (test series 2) the shear creep tests were also loaded with a normal stress of 20 kPa. However, all the tests were carried out with the same GCL sample. In the first test of this series, a pre-hydrated sample which had been under 20 kPa was subjected to a tangential stress of 47.3 kPa. This corresponds to a 70% loading rate. As a result of the pre-hydration under 20 kPa and a simultaneous shear pre-stressing (at a stress level of 65%), no initial shear deformations were measured in test series 2. It was therefore the immediate shear deformations of stationary creep that were measured.

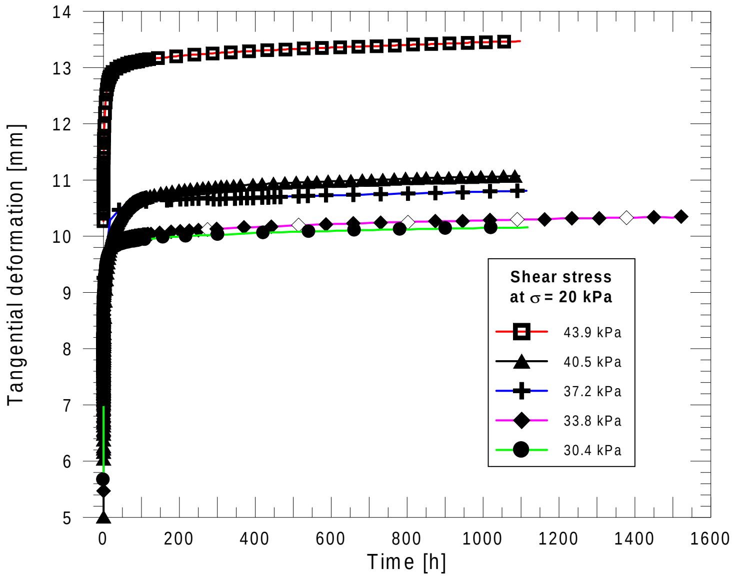

Figure 6. Absolute readings for shear deformation in test series 1.

After approx. 1,000 hours, the same sample was again subjected to the next highest tangential stress of 50.7 kPa, corresponding to a loading rate of 75%. Within the following 1,000 hours, the shear deformations increased by approx. 1 mm.

Subsequently, the stress was fully removed from the sample for a short period, so that the needle plates could be re-set before being subjected to a loading rate of 80%. In spite of re-setting the nail plates, a shear deformation was again very quickly produced after re-starting with the same samples. This deformation resulted approx. 3 mm lower, when measured absolutely. In spite of re-starting, the typical shear creep behaviour determined in the previous tests was again seen after 10 hours at the latest.

After the test with a loading rate of 80% over a stress period of 1,000 hours, a further test was carried out at 85% loading rate, also for 1,000 hours. Finally, the samples were examined, each for only a few days, at 90 or 95% loading rates. No shear creep failure occurred in any of the shear creep tests carried out on stitch-bonded GCLs. As with Figure 6, there is no transition to accelerated creep in the linear plotting of results in Figure 7.

However, this looks different when the results are plotted over the period logarithmically. This shows that the tests with the higher loading rates (80 to 90%) show the start of accelerated shear creep. Although no shear failure occurred in the shear creep tests shown within each 1,000-hour period of shear stress, even at the very high loading rates, an attempt is made in the next section to make a forecast on the basis of the available data as to when failure times will occur under each loading rate.

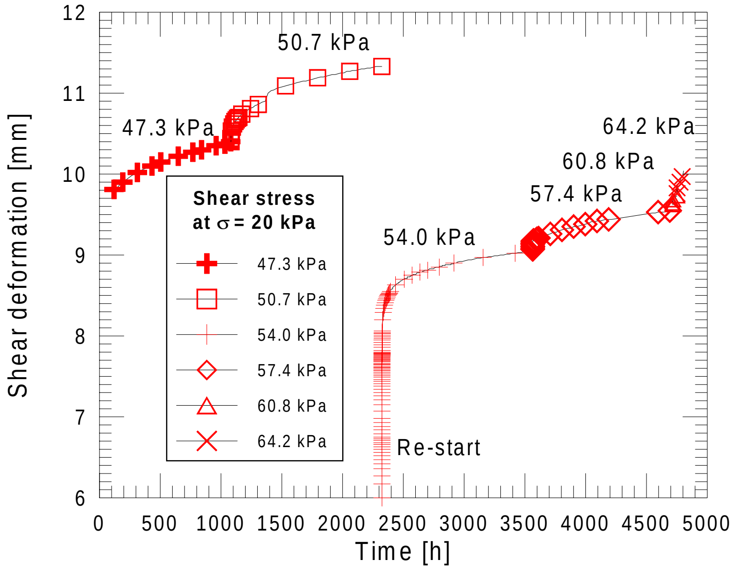

Figure 7. Absolute figures for shear deformation in test series 2.

5 PREDICTION OF LONG-TERM SHEAR STRENGTH

It is necessary to determine long-term shear strength under real, measured failure times. However, no shear failure ever occurred here within a reasonable period of time. The forecast given here is speculative in as much as a compensating curve that best displayed the behaviour of the figures measured was sought for each shear deformation curve. Compensating curves with an exponential function were selected for most curves as the best approach to the figures. Similar procedures were used for tensile creep tests.

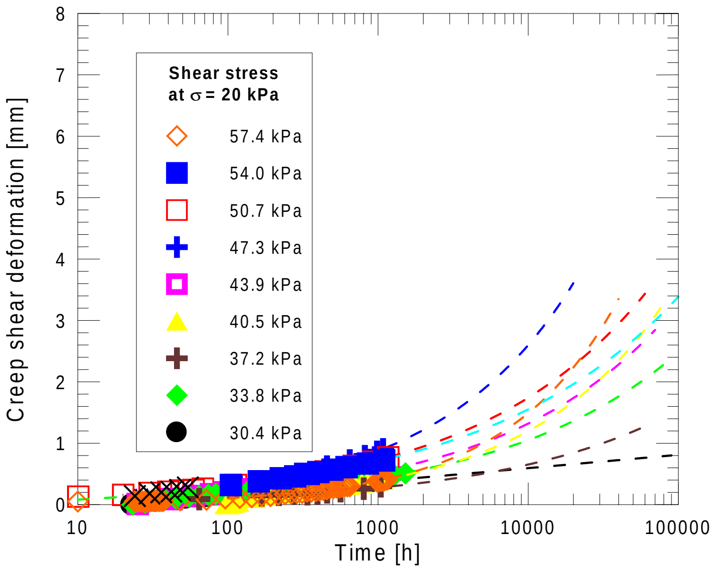

Figure 8. Extrapolation of creep shear deformations.

Figure 8 shows all results summarised in one diagram. However, the creep shear deformations have been plotted over the period of stress and not the total shear deformations. Creep shear deformations are here to be understood as the shear deformations which occurred, chronologically seen, after 1-minute shear stress, i.e. the creep shear deformations are the measured absolute shear deformations less the shear deformations occurring after 1 minute of stress. A similar procedure is used with tensile creep tests.

An attempt is made, using logarithmic compensating curves, to arrive at a forecast on further shear deformation dependent on the application of shear stress, similar to extrapolations with tensile creep tests. To achieve the forecast failure times, extrapolations of up to five decimal powers are necessary, because of the high resistance to creep failure. Naturally this is somewhat uncertain, as all chronological extrapolations greater than one decimal power are open to criticism. However, this example is intended to show the way that the long-term shear strength of GCLs may be determined. It goes without saying that the shear creep tests must be carried out with tangential stresses that really cause shear creep failure in the GCLs in reasonable periods of time. Because of the high shear creep resistance of the stitch-bonded GCL tested, something not expected to this high degree at the start of the series of tests, this was not possible here.

At the current point of time, there are no other test results with even higher tangential stresses. Carrying out the tests is a very protracted matter. Further tests of the type described must therefore be carried out, in order to achieve actual shear creep failure points in periods of less than 1,000 hours.

A shear deformation of 20 mm was set as the limit of shear deformation for the example of determining long-term shear strength subsequently described. As the maximum shear stress in short-term shear box tests is reached with a shear deformation of approx. 30 mm, the above estimate was on the safe side. The forecast failure times thus achieved are plotted in Figure 9 in relation to the shear stress. This depiction of the results shows that the shear stresses permissible for the GCL decrease as the stress duration increases. If a logarithmic compensating curve is then drawn between the points plotted, the connection becomes clearer. It becomes possible to derive the shear stress which the GCL can accept for a pre-determined period of time from the diagram. For the example shown, a long-term shear strength of 51 kPa is given for a measurement period of e.g. 10^6 hours (114 years).

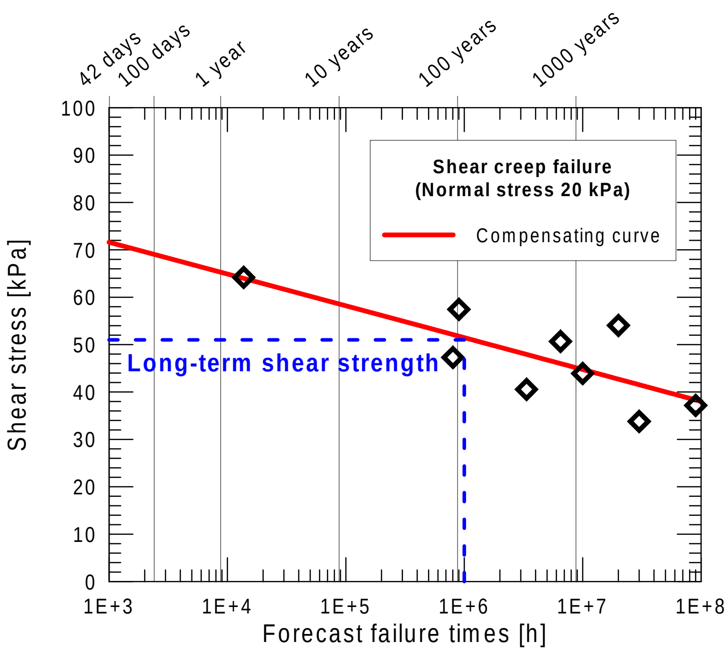

Figure 9. Diagram of shear creep failure with forecast failure times.

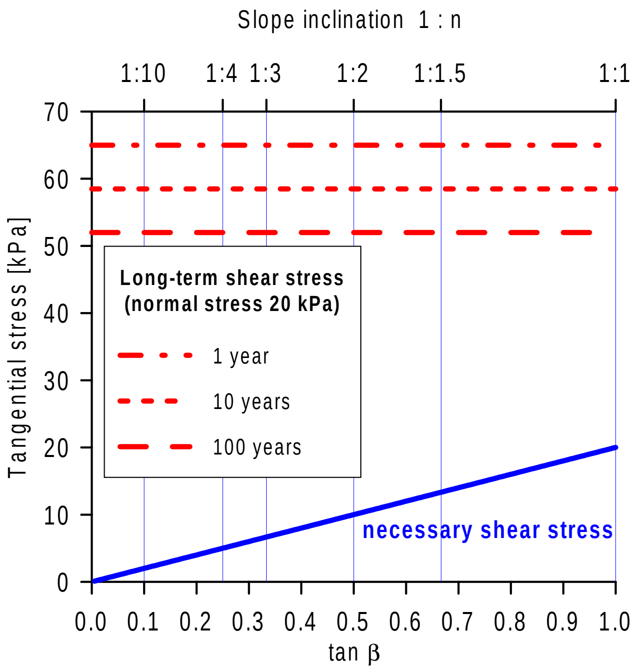

Figure 10. Depiction of long-term shear strength dependent on creep for different periods of measurement and the necessary shear stress for a normal stress of 20 kPa.

Figure 10 makes clear that the creep-related long-term shear strength thus attained for long periods of measurement still contains a considerable safety margin where the shear stresses actually required on landfill slopes are concerned. The shear stresses are plotted here in relation to the tangent of the slope inclination for a normal stress of 20 kPa. The representation shows that while the safety interval between the long-term shear strength and the necessary shear stress decreases as the slope inclination increases, it is still considerable.

6 CONCLUDING REMARKS

The shear creep behaviour of GCLs is discussed in detail. From this it is clear that no statement on the long-term shear behaviour of GCLs is possible from short-term shear tests alone. Not even long-term tests with tilting plates or field tests will help. Tests must be carried out with a shear creep failure being forced. This makes it possible - as is also standard practice for geosynthetic reinforcing material - to produce a forecast for the long-term shear strength of GCLs.

A stitch-bonded GCL is subjected to various tangential stresses in power controlled shear creep tests at a normal stress of 20 kPa in 11 different individual tests, each of over 1,000 hours. Shear creep failure of the GCL was not obtained.

The procedure for establishing the long-term shear strength dependent on creep is presented.

The long-term shear strength dependent on creep is determined using extrapolation methods known (and recognised) from tensile creep tests.

The tests carried out show that it is necessary to select higher loading rates (80 to 90% of short term shear strength), in order to achieve shear creep failure in a reasonable period of time. This applies to the GCL tested here.

Using the newly-developed test equipment shown here and the associated procedures, reliable forecasts of the long-term shear strength of GCLs may be produced.

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