Long term testing of geomembranes and geotextiles under shear stress

S. Seeger, H. Böhm, G. Söhring & W. Müller
Federal Institute of Materials Research and Testing (BAM), Berlin, Germany

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ABSTRACT: Geomembranes with high friction angles, so called textured sheets, and also other geosynthetics like geocomposite clay liners (GCL) are frequently used in steep slopes of landfill caps and other applications. Normally, knowledge of the friction parameters in contact with other layers or soil, as measured by short term shear box tests, is felt to be sufficient for a safe design. In many applications, however, the long term slope stability depends heavily on the ability of these geosynthetics to sustain shear stress over a very long period of time. Thus, besides friction, the durability, creep behavior and stress crack resistance of the geosynthetics and their polymers must be considered in order to end up with a safe design. For this purpose a novel long term shear test method was worked out. It gives some feedback for manufacturers in order to improve their products and allows of a risk assessment for application. The paper outlines the test and its application to geosynthetics and presents results on textured geomembranes.

1 INTRODUCTION

Landfill caps are typical applications where geosynthetics like textured geomembranes, geocomposite clay liners (GCL) and also geocomposite drains (GCD) permanently sustain shear stress when applied in slopes, as illustrated on the left of Figure 1.

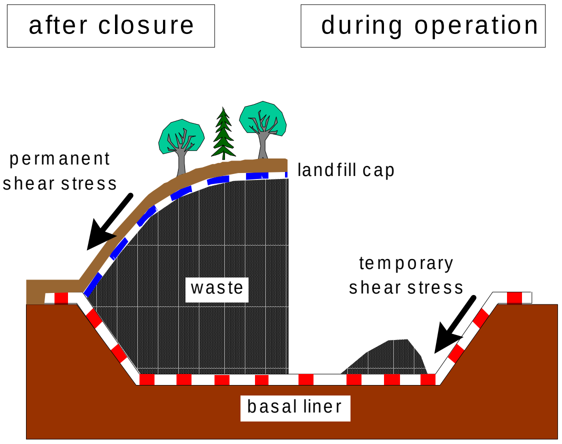

Figure 1. Permanent shear stress in a landfill cap

The shear stress is evoked by the weight of drains and earthen material on top of the geosynthetic. In contrast, shear stress acting on geosynthetics in the base of landfills, as shown on the right of Figure 1, may occur temporarily only during operation of the landfill, because the waste body is - at least in the long run - stable in itself and supports the geosynthetic once the landfill is filled and settlements in the waste have diminished.

For the safe application of geosynthetics under permanent shear stress in slopes the knowledge of the frictional behaviour only, as normally measured by short term shear box testing, is not sufficient. This can be seen from the following examples.

1.1 *Textured geomembranes*

Several types of geomembranes are available. There are embossed sheets, and also those textured geomembranes, whose surfaces are roughened in a subsequent manufacturing process in order to increase the friction angle in contact with mineral or geosynthetic layers. For the latter type techniques have been developed by several geomembrane manufacturers for application of small polyolefin particles to the geomembrane surface. Frequently, different resins are used for sheet and particles. Both, the manufacturing processes and the variety of resins used makes the evaluation of the long term behaviour of these sheets a difficult, but necessary task. Therefore this paper mainly refers to the latter type of textured sheets. The embossed sheets, however, are considered as less critical with respect to their long term properties because they are made of one resin and in one single step only. However, stress cracking at local stress concentrations is a failure mode one should think of for embossed sheets.

The effective friction angle between a textured sheet and soil or a geotextile, as usually measured in the lab via short term friction tests, only reflects a property of the new product. The long term slope stability, however, depends heavily on the ability of the texturing, i.e. the particles, to permanently, or at least in the foreseeable future, sustain shear stress. The particles at the sheet surface must not yield to the shear stress acting on them in order to ensure friction at a constant level. The adhesion of polymer particles to the sheet surface may, depending on manufacturing conditions and choice of resins, drastically be compromised by aging, creep and stress cracking. Either of these detrimental mechanisms could occur in particles or at their interfaces with the geomembrane and could potentially contribute to a slow but steady loss of adhesion of particles. With time, the friction may fall short of a critical limit. Certainly this causes a sudden total loss of stability and subsequent slope failure.

Thus, the lasting adhesion of the texturing is a key property of textured sheets, although this property is neither paid much attention to by civil engineers, nor commonly tested up to now. However, a textured sheet which passes the usual short term friction test may not necessarily also prove to have a good long term adhesion of the texturing. This emphasizes the need for a long term shear test which gives a feedback to optimum manufacturing and choice of resins and allows estimation of margins of safety.

1.2 *Geocomposite clay liners*

GCL usually consist of an upper and lower geotextile, sandwiching a bentonite layer. The geotextiles are connected via stitch bonding or needle bonding. Normally, the shear parameters at the interfaces of the GCL to soil or other geotextiles are measured via short term testing. Sometimes also the internal shear strength is measured by a short term peel test.

However, provided that the interface and internal shear strength has been proven sufficient for a certain application by short term testing, the question is still open whether in the long run the internal shear strength maintains to be sufficient too. There is some resemblance to textured sheets: In the long run, the internal shear strength of a GCL in a steep slope depends solely on the ability of the connecting fibers (or yarns) to permanently sustain shear stress. It depends therefore on density (number per m^2), tenacity and long term durability of these fibers. With respect to the slope stability the contribution of the bentonite, saturated with moisture, is rather detrimental because of its lubrication effect. Once the connecting fibers start to fail this will sooner or later result in a total loss of stability and a slope failure. A breakdown of these fibers may be caused by breakage due to oxidation, creep or environmental stress cracking, and also by slow disentanglement. Even predamaging during production may contribute to a premature breakdown. Therefore, besides friction at the interfaces the long term internal shear strength of a GCL deserves full attention as a key property in order to found the design and application in slopes on solid knowledge and to permanently ensure slope stability.

The real stress acting on connecting fibers or yarns in a GCL is hardly predictable for the reason being the non uniform distributions of tensile stresses and creep. Therefore, single fiber testing as well as short term peel tests of GCLs may be helpful to clarify general limits, distinguish fibers and resins and provide data for design and construction, but only allow a limited clue to the long term behaviour of a GCL in a slope. This second example therefore again emphasizes the need for a test method which enables the evaluation of the long term behaviour of GCLs under realistic long term shear stress.

2 TEST DESIGN

The design of the long term shear test for geosynthetics is shown below in Figure 2. It complies with the following specifications, which has been considered important at the starting point of the development of the test method: Simulation of typical stresses (compression, normal stress and shear stress) in realistic proportions, acting on an geosynthetic in a slope.

1. Simulation of realistic speeds of deformation/creep.
2. Accelerated test conditions, i.e. specimen are immersed in water or any other liquid medium at elevated temperatures ≤ 80 °C.
3. Two-dimensional observation of creep and deformation in order to calculate the shear deformation of the specimen.
4. Test stand is handy and not expensive. This allows of good time management, small occupied space and reduction of the statistical scatter of data by parallel running of up to twenty test stands.

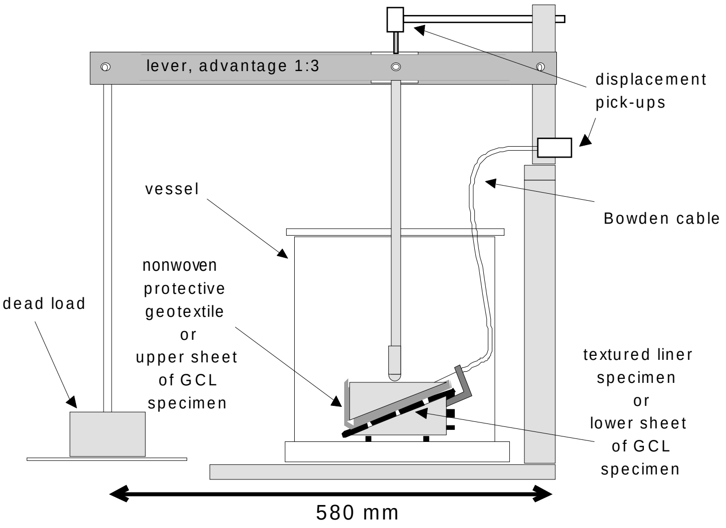

Figure 2. Schematic view of the long term shear test stand

The geosynthetic specimen is sandwiched in between a pair of stainless steel wedges. Each wedge measures 120 mm by 120 mm at its base while its height is 4.8 mm, resulting in a angle of inclination of 1 to 2.5 or 21.8 degrees. The specimen, mounted to the wedges, is positioned in the middle of a stainless steel vessel of approximately 13 liter volume. The vessel is equipped with an 300 VA electrical heating element. A cap reduces water losses due to evaporation. The maximum temperature is 80°C with an error of ±1 °C. Deionized water is always used as test medium, although other liquids may also be possible. As shown in Figure 2, the dead load acts on the upper wedge via a levers system. Normally, an area load of 50 kN/m^2 is applied in accordance with the typical upper limit in slopes of landfill caps. The angle of inclination, the load, the temperature and the test liquid may of course vary according to needs.

The shear strain is registered by two displacement pick-ups positioned as shown in Figure 2. The first is mounted on top of the vertical rod and records the vertical movement of the upper wedge. The other is placed outside the vessel and measures displacement in the shear plane via a Bowden cable, which is required as it is not possible to submerge the pick-up into the hot water. The vertical gauge only is used for testing of textured sheets.

3 TESTS WITH TEXTURED SHEETS

The specimens for textured sheets have been prepared as follows: Coupons (120 x 150 mm²) have been mounted on the lower steel wedge and then covered with a piece of a nonwoven protective geotextile, fastened to the upper wedge. Only one type of nonwoven (1200 g/m^2, polypropylene, less soft face towards textured sheet) was used for the tests. The respective machine directions of the sheet coupons as well as of the nonwovens coincided and pointed downwards. The sheets tested have been textured on both sides by the manufacturer. As not unusual for geomembranes, faces differed in appearance, one side was mat while the other was shiny. Specimens have always been tested with mat side up. The load was applied immediately with the specimen immersed into cold water and the set point of 80°C was reached after approximately 4 hours.

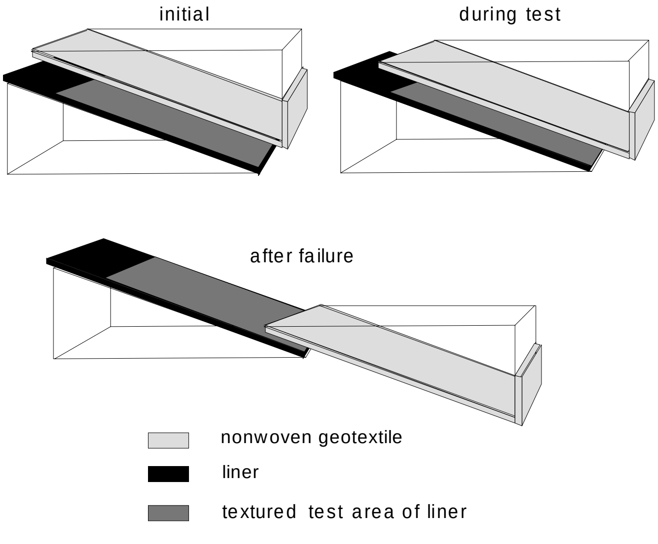

Figure 3. Textured sheet sample in test. Schematic view of the specimen and the wedges in the initial state, during test and after failure.

It is important to note, that during the test only the friction at the interface between the specimen test area and the geotextile prevented the upper wedge from completely sliding down. However, once the friction disappears due to failure of the texturing, a complete slide occurs within few seconds, as indicated in Figure 3.

A downward movement of the upper wedge occurs during the test. Three mechanisms contribute to it: Firstly, in order to compensate the shear stress, the nonwoven undergoes an immediate shear deformation and an immediate but limited slide downward. Secondly, the normal force slowly compresses the nonwoven. Thirdly, the nonwoven may creep downward extremely slow. In practice, the first contribution is by far the largest, but fades out within less than a day. The last contribution is negligible even at 80°C, as can been seen from a comparison of data for nonwovens, compressed without shear, to the data from the shear tests

Therefore, after an initial phase only the compression of the nonwoven is observable until the upper wedge slides completely due to a loss of friction. The immediate slide, however, reduces the overlap between upper and lower wedge and this causes an unwanted increase of the shear stress. The following solution was found to keep the shear stress constant: The texturing was partly scraped off the specimen surface, as indicated in Figure 3, leaving a rectangular test area of 0.0132 m^2 (110 x 120 mm^2) unchanged. Hence, the shear stress is sustained only within this textured test area, while in the smoothened part of the surface the friction is drastically reduced to a negligible level. Therefore, despite a reduced overlap between upper and lower wedge the shear stress remains constant in the test area because it is always completely covered with the nonwoven. Minor changes of the effective shear stress due to a slight deviation of the rod from verticality were found to be negligible.

The tests are performed under accelerated conditions: i. e. in purified water at 80°C. For each specimen the time to failure, i.e. the time to a complete slip off is measured and the vertical component of the movement of the upper wedge is recorded automatically. In order to determine the loss of texture material each specimen was weighed before and after testing.

Table 1. Numbering of the samples tested

Table 1						
specimen type	A	B	C	D	E	F
texturing						
resin	2	2	3	1	5	5
batch	B1	B2	-	-	B1	B2
Sheet						
resin	1	1	1	4	1	1

For the test program several textured sheets from one manufacturer have been selected, which are made of different polyethylene resins and batches. While the HDPE-resins for the sheets are widely used also by other producers, the resins and batches for the texturing have been chosen by the manufacturer in order to comply with the specific requirements of its production method. All samples have been collected during normal production shifts. Specimens are hardly distinguishable with the naked eyes because the amount and appearance of particles attached to their surfaces is always the same. The following Table 1 gives an overview on the specimen used in the test. Numbers indicate different PE resins. Resin no. 1 was used for the sheet as well as for the texture. B1 and B2 are different carbon black batches.

4 TEST RESULTS

Figure 4 as an example shows a typical vertical displacement curve of the upper wedge during a test run as recorded by the vertical displacement pick-up. As explained above, the main contribution comes from the initial straining of the nonwoven geotextile, as indicated in the diagram. The specimen failed after 11 days by a sudden complete slip off.

The results of the measurements are shown in Figure 5. No curve is drawn, however, for specimen types E and F. This is simply due to the remarkable fact that no failure has been observed for these samples after more than 550 days of testing, although the applied area load of 50 kN/m^2 is in the upper range of typical values for landfill caps, and accelerating conditions are used in the test as described above.

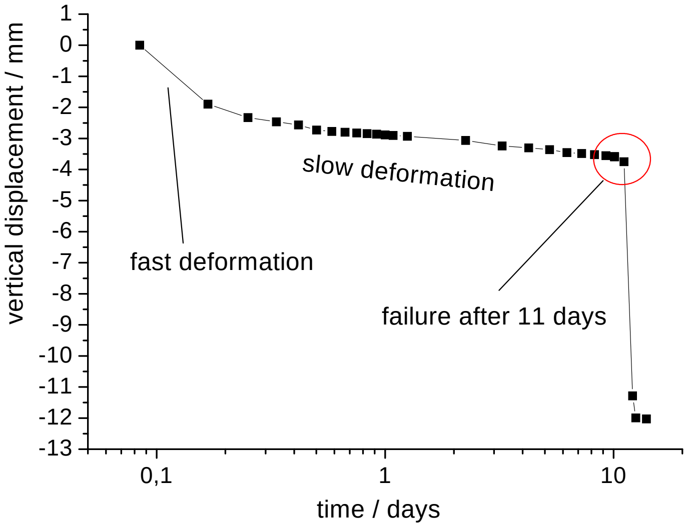

Figure 4. Vertical displacement of upper wedge

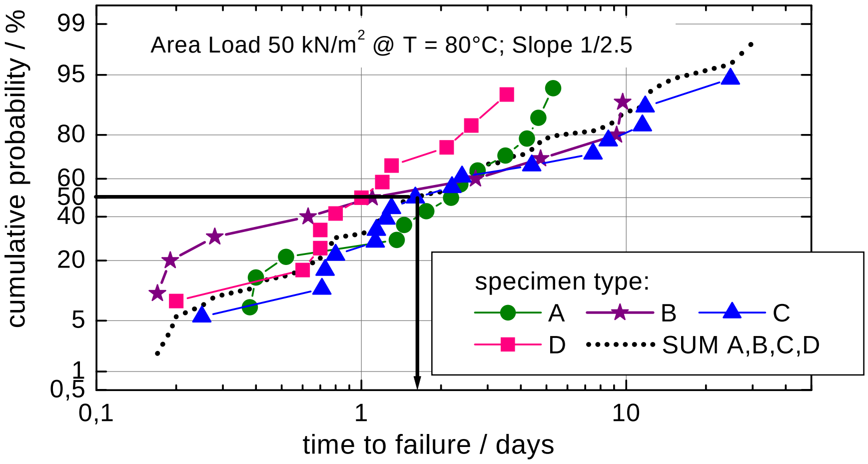

Figure 5. Experimental results – Cumulative probability of failure versus logarithm of time to failure

In Figure 5 for each type of specimen the cumulative probability of failure times is displayed on a probability scale over a log-time scale. The cumulative probability was calculated by assuming that each measured failure time represents $^{100}/_{n}$ percent of the population of n specimen of type A to

D respectively. The dotted line combines all measured data: As indicated by the bold line and arrow, 50% of all specimen failed after only 1.6 days, while 10% failed after 0.3 days and nearly all (98%) failed after 30 days. The same method is used e.g. for the analysis of internal pressure tests on polyolefin pipes.

Data points plotting a straight line on a probability scale indicate a normal or log-normal distribution of failure times if a normal scale or log scale abscissa is used respectively. As can be seen from the plot, the linearity of data points is fairly good, when assuming a log-normal distribution of failure times. This type of distribution is also characteristic of failure times of polyethylene pipes under internal pressure. It indicates, that several independent contributions to a certain failure mode prevail, each with its own characteristic.

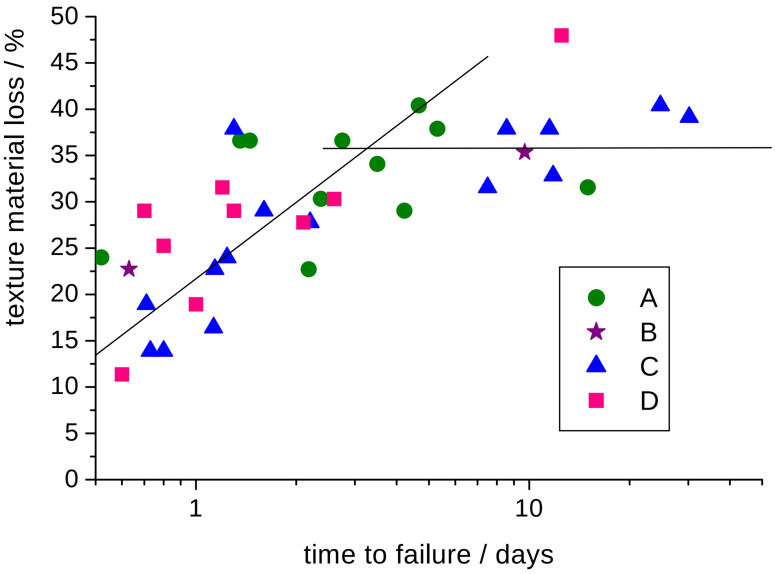

Figure 6. Experimental results - loss of texture material (wt.-%) versus logarithm of times to failure

The failure of the specimen was accompanied by a partial loss of texture material, distributed evenly over the test area. As indicated in Figure 6 by two trend lines, the loss increases with failure time in the beginning but then seems to saturate at a value of approximately 35 wt.-%.

5 DISCUSSION, CONCLUSION AND OUTLOOK

The long term shear test has proven to be an appropriate tool for the selection of durable textured sheets. It is evident, that textured sheets according to specimens E and F are by far more durable than all other products in the test. After more than 500 days of testing a breakdown of the PP nonwoven geotextile due to aging (Müller, Jakob 2000) is likely, rather than a failure of the textured sheet. Sheets E and F are therefore regarded to be suitable for long time use in slopes. In contrast, the poor performance of sample types A to D strongly supports the importance of careful selection of appropriate textured sheets via long term testing. By comparison: In the internal pressure test polyolefin pipes, made of selected, modern HDPE geomembrane resins reveal failure times of more than 417 days (10^4 h) at 80°C, when moderately pressurized. Pipes made of earlier types of resins, fail after significantly shorter times.

The investigation are continued to clarify failure mechanisms, to study dependence of failure time on temperature and load, and to finally establish an extrapolation method.

ISO DIS 9080:1999 describes a standard extrapolation method for service time estimates from pipe pressure date of tests on HDPE pipes (Schulte 1997). Empirical extrapolation factors, which give the allowable range of extrapolations, have been determined by lots of experiments. The extrapolation factor between 80 °C testing temperature and ambient temperature (20 °C) was found to be 10^2. If e.g. the observed failure time at a given stress level and at 80 °C is one year, the allowable upper estimate of the lifetime at ambient temperature is 100 years.

A lot more experience is necessary to establish such an extrapolation method also for long term shear testing of textured sheets. However, leaning on the comprehensive experience with pipe testing we tentatively suggest that textured sheets (and other geosynthetics) should achieve failure times of more than one year at moderate stresses in the long term shear test at 80 °C. For the time being, textured geomembranes which meet this requirement are regarded as appropriate for long term application under permanent shear stress.

The successful use of the long term shear test for textured sheets strongly encourages its application for the investigation of other geosynthetics like GCL and GCD. First successful attempts to investigate GCL with this test have already been made in the BAM and will be continued in a research program aiming at clarification of failure mechanisms, investigation of the dependence of temperature and load, extrapolation of data and correlation of results with short term friction data.

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