LONG-TERM SHEAR STRENGTH OF MULTILAYER GEOSYNTHETICS

W. Müller, S. Seeger, M. Thies, C. Gerloff
Federal Institute for Materials Research and Testing (BAM), Berlin, Germany

ABSTRACT: Geosynthetics often have a sandwich-like multilayer structure, e. g. GCLs, textured GMs and GCDs. Different components made of diverse resins are bonded by various methods. When used on long and steep slopes and covered with thick soil layers, the geosynthetics are permanently exposed to a combined action of compression and shear. Landfill cappings are characteristic for these loading conditions. Under such conditions the slope stability of the overall capping systems strongly depends on the long-term internal shear strength of the multilayer geosynthetics used. We developed a test methodology to study this long-term shear behaviour. The focus was not only on creep, as it is normally done, instead, our method comprises all kinds of ageing effects: Our test equipment allows for the measurement of creep curves and times to failure at high temperatures and in different media. In this paper we summarize the main findings of our research: The long-term shear strength of multilayer geosynthetics strongly depends on the type of resin as well as on details of the product design and manufacturing. Even minor modifications may have large influence on times to failure and failure mode. On the other hand, index values of short-term shear strength (e.g. peel strength) do not reflect the actual long-term shear strength, and hence do not provide reliable dimensioning data for product design and choice of resins. The long-term shear strength can substantially be influenced by both, test conditions and general conditions on site. With an appropriate product design of the geosynthetic and choice of resins, based on long term test data, extremely long service lifetimes might be achieved even under severe loading conditions. However, the often suggested approach, namely, restriction to short term testing only and application of factors of safety, is challenged by our results.

1 INTRODUCTION

Geosynthetics frequently are made up of several components combined in a multilayer configuration. Examples of such products include geomembranes (GM) with texturing applied after fabrication (smooth base sheet with heat bonded texture particles) (Müller 2001), geosynthetic clay liners (GCL) - bentonite powder encased between two geotextile layers (GT) and the GTnw and/or GTw connected by fibres or yarns (Thies 2002) - and geocomposite drains (GCD) which are normally made up of a filter layer, a highly permeable core and a protective layer connected by various bonding techniques (Müller 2002a). When geosynthetic products of these types are used to line slopes, the sliding stability of the overall cap lining system is dependent on the frictional forces between the geosynthetic product and the adjacent lining system components as well as the internal shear strength within the geosynthetic itself. The actual shear stress encountered in a specific application depends on the configuration of the lining system. If the geosynthetic product is installed over an uneven subgrade and constrained sufficiently by the covering soil, the adjacent surfaces will interlock, in which case shear and frictional forces are not significant factors. However in most cases - particularly in composite lining systems made up of several geosynthetic elements - clearly defined sliding planes are present and forces acting down the incline must be born fully by the internal shear strength of the lining system elements and the frictional forces at the interfaces between them.

Shear strength of geosynthetic products is normally determined in shear box testing (Blümel 1994). In this procedure, the upper and lower surfaces of the product tested are fixed in place on the respective halves of the shear box apparatus, which are compressed by a defined normal load and moved apart at constant speed. The resultant shear force is recorded as a function of displacement, allowing determination of peak shear force. A similar data plot can be obtained for peel strength, which is measured by peeling the samples in a wide width tensile test. Peel strength is closely related to shear strength (von Maubeuge 2002), much easier to measure and therefore products are optimised with respect to short-term peel strength.

Short-term test data of this kind involving simple experimental procedures is frequently used as dimensioning data - modified by safety factors as appropriate - in geotechnical structural design. For all building materials, short-term (i.e. high-speed) strength can differ significantly from the actual long-term strength observed under field conditions. This is observed in particular in building materials with pronounced visco-elastic behaviour such as thermoplastics (Müller 2002a). In addition all building materials are subject over time to ageing processes (corrosion, stress cracking, morphological changes, oxidation, etc.), which affect physical strength. The resultant strength reduction varies greatly over time and cannot be reliably characterized by safety factors. Aside from shoddy workmanship, insufficient differentiation between short-term and long-term properties of construction materials is the single most common cause of structural failure with often dramatic consequences.

The definition of a safety factor implies that during the service lifetime of a construction a certain property of the construction material - e.g. shear strength - will not fall short of a well defined fraction of its initial value. However the essence of ageing processes is that materials properties will steadily or suddenly change with time and sooner or later will fall below such well defined limits. Therefore, with the definition of a certain factor of safety necessarily a certain lifetime expectation of the material is defined implicitly. The use of safety factors with geosynthetics relies on the (often unspoken) assumption that in normal geotechnical applications the lifetime of plastic material is much larger than the required service lifetime of the geotechnical construction (typically some decades). However, there are long-term geotechnical applications, like landfill lining, where the above assumption is certainly not valid and, hence, the ageing behaviour of the geosynthetic products has to be investigated explicitly.

The following text will discuss a test procedure for long-term shear strength of multilayer geosynthetics (e.g. GCLs, GCD and textured GMs) as well as some experimental results obtained to date for textured GMs and GCLs. The results obtained in the past have been published in detail in literature sources (Seeger 2000), (Seeger 2001) and (Thies 2002). Therefore this paper will only give an update and will - above all - focus on the presentation and illustration of some essential synoptic conclusions following from all the test results to date. Final test results for GCDs are not available at the present time, as this testing has only recently begun.

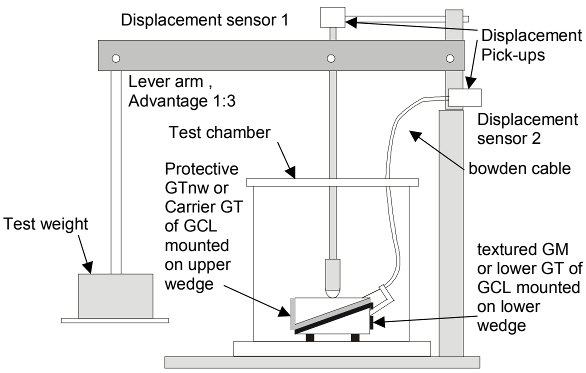

Figure 1 Schematic illustration of long-term shear test stand

Figure 2 Overall view of testing device

2 TEST PROCEDURE

Shear strength testing of geosynthetic structural components is conducted in long-term test stands which subject the part to physical stress at high temperature in a liquid or gas test environment until failure occurs. By varying the test conditions, functional relationships can be established with time to failure, allowing extrapolation of expected service lifetime under field conditions. Burst pressure testing of plastic pipes for determination of permissible long-term line pressure is perhaps the most widely recognized long-term test procedure in the plastics field. Using this type of test as a guide, we designed testing stands for evaluation of long-term behaviour of geosynthetics under shear stress (Figure 1 to 3).

Figure 3 Specimen holder mounted with textured GM specimen and geotextile specimens as friction partner

A specimen (apprx. 12 cm x 13 cm) of the product to be evaluated is fixed between two steel wedges (standard incline of wedges: 21.8°, corresponds to slope of 1 : 2.5) as shown in Figure 3. A lever mechanism is used to exert a force on the upper wedge, which is representative for loading in cap liner applications. The resultant force component down the incline is the shear force between the upper and lower surfaces of the specimen. The testing device is housed in a controlled-temperature water bath (T_{max} = 80 °C). As is the case in long-term pipe burst testing, the high test temperature accelerates creep deformation, stress crack formation and oxidative degradation.

The test parameters, which can be varied in the test, are vertical load (or the vertical load/shear load ratio) and temperature. Other test environments can be used in place of water if appropriate for specific applications. Two high precision ($\Delta s \leq 0.1$ mm) displacement sensors automatically monitor vertical displacement of the upper wedge and displacement in the shear plane. The experimental data is used to calculate the compression and shear deformation of the geosynthetic in the incline plane. Failure of the test specimen - e.g. displacement of geotextile layers after separation of the connecting fibres - is documented regardless of whether failure occurs abruptly or over a prolonged period of time.

In testing of textured GMs, the GM and the contacting geotextile are screwed onto the lower and upper wedges respectively to fix them in place. When the wedges are placed together, sliding is prevented by the friction between the texturing particles and the geotextile. In testing of GCLs or GCDs, firm contact to the wedge is ensured by full-surface anchoring on a textured layer permanently mounted on its surface. The textured layers used were textured GMs, metal food graters or nail plates (Figure 4).

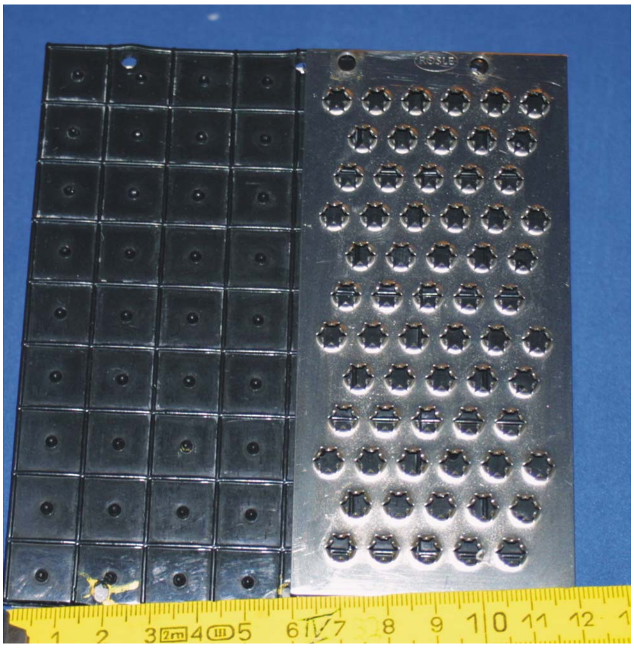

Figure 4 Two textured friction partners, which were mounted onto the wedges ensuring high friction and firm contact to GCLs or GCDs

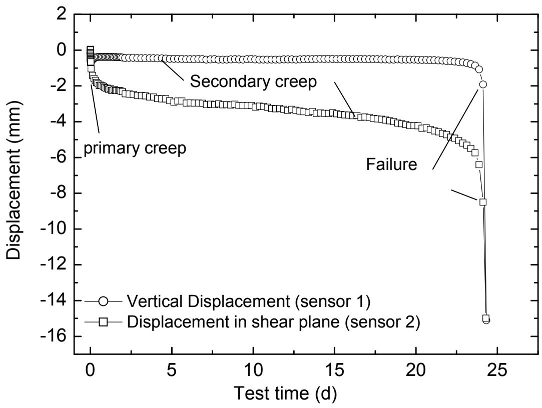

Figure 5 Examples of displacement vs. time curves as monitored by displacement sensors

Figure 5 illustrates typical displacement vs. time plots measured in the test. As shown by the graphs, an initial phase of rapid deformation (primary creep) in response to the compressive load is followed by a stable phase of gradual, continuous deformation (secondary creep). Shortly before failure, the speed of deformation increases sharply (tertiary creep or materials degradation) and failure occurs.

Times to failures achieved in this accelerated test can be used to predict service lifetime at normal ambient temperatures. Ageing can manifest itself gradually and continuously over time - when the chemical and physical processes associated with ageing immediately affect the function of the material. Ageing can also occur very abruptly - when degradation is initially hidden and affects function only after a certain degree of accumulation has occurred. An example of the latter case is gradual depletion of antioxidants as is frequently found in polyolefin materials. The change in properties observed over time can often be expressed as an exponential function:

$$P(t) = P_0 e^{-kt} \tag{1}$$

When a certain threshold value P_s is attained under the stressing encountered, failure occurs. The time to failure t_s can therefore be expressed as:

$$t_S = \frac{1}{k} \ln \frac{P_0}{P_S} \tag{2}$$

If the ageing process mechanism does not change over the temperature interval considered, the time to failure vs. temperature function is governed essentially by the speed of ageing k. The function is normally a simple Arrhenius dependency:

$$k = k_0 e^{-E/RT} \tag{3}$$

Such simple equations can satisfactorily characterize the macroscopic property changes even if the molecular processes causing them on a microscopic scale are extremely complicated and by no means obey simple kinetic relationships. This can be illustrated (more so than explained) by a simple chain of reasoning. A process causing a given ageing manifestation can be considered to basically consist of many localized degradation processes occurring in discrete small, but still macroscopic subsystems. In each local process a transient ordered non-equilibrium state in the subsystem considered undergoes transition with a certain degradation rate r to a stable equilibrium state. Each local process begins in its subsystem only after the subsystem has a certain internal energy E, the apparent activation energy. $N(E)$ is the number of subsystems activated in this manner. In any given time interval Δt, ΔN subsystems will have undergone transition:

$$\Delta N = r \cdot N(E) \cdot \Delta t \tag{4}$$

When the subsystem is at thermal equilibrium with its surroundings at temperature T, the probability w of a given subsystem having internal energy E can be expressed as:

$$w = \frac{e^{-E/RT}}{Z(T)} \tag{5}$$

Where R is the universal gas constant (8.314 J/mol K) and $Z(T)$ is a (temperature-dependent) normalization factor. This equation is a universally valid thermostatistic relationship. $N(E)$ can then be expressed as:

$$N(E) = \frac{e^{-E/RT}}{Z(T)} N \tag{6}$$

Where N is the total number of subsystems still in the initial state. Substituting equation (6) into equation (4), the rate of change of N is:

$$\frac{dN}{dt} = \frac{r \cdot e^{-E/RT}}{Z(T)} N \tag{7}$$

P is proportional to *N*. The exponential relationship for *P* as a function of time given in equation (1) with the relationship for the speed *k* as a function of temperature given in equation (3) therefore follows from equation (7). Time to failure as a function of temperature is obtained by substituting the Arrhenius equation (3) into equation (2):

$$t_S(T) = \left(\frac{1}{k_0} \ln \frac{P_0}{P_S} \right) e^{E/RT} \qquad (8)$$

As can be seen from equation (8), a plot of logarithm of time to failure versus reciprocal absolute temperature (this is referred to as an Arrhenius diagram) is a linear relationship, which can be extrapolated to application temperatures. In accordance with equation (7), k_0 in equation (3) should also be temperature dependent. However when $RT<E$ - which is normally the case - this temperature dependence is very slight and is almost always negligible in comparison to the factor exp($-E/RT$). In the event of slight divergency from the Arrhenius linear relationship, a better data fit is obtained by the equation $k = T^n \exp(-E/RT)$, where *n* is a small negative or positive coefficient.

As noted previously, an essential prerequisite for any extrapolation is that the mechanism of the ageing process does not change over the temperature interval considered. For many plastics this is not the case at temperatures above 100 °C. In polyethylene for example, the degree of crystallinity - a characteristic, which substantially affects many processes - decreases considerably above 100 °C; in some polypropylene resins the effectiveness of stabilizers changes significantly at around 100 °C. Other abrupt changes at or near this temperature are known as well and could be given as further examples. As a result, Arrhenius extrapolation of data determined at test temperatures above 100 °C is not normally meaningful for prediction of performance at normal application temperatures. Testing must be conducted at lower temperatures as well - with the attendant disadvantage of increased test duration.

The apparent activation energy of many chemical and physical processes is somewhere in the vicinity of 50 kJ/mol. At normal application temperatures equation (8) gives rise to the Van't Hoff rule for chemical reactions - known since the end of the 19th century - which states that increasing temperature by 10 °C increases reaction rate by a factor of 2 - 3. This rule is astonishingly accurate for many ageing processes in plastics. For geosynthetic thermoplastics the factor is empirically found to be around 2.5. Therefore to reliably demonstrate service lifetimes of at least 100 years at typical underground application temperatures of 15-20 °C, tests conducted at 80 °C must be carried out for at least 1 year.

3 RESULTS AND DISCUSSION

3.1 *Products*

To discuss our main findings we present test results for textured GMs and GCLs made of different resins and produced with modification in the manufacturing process.

For example, textured GMs were tested which had been coated by a spray gun with two different resins (in this paper labelled A and B) of low density polyethylene with comparable density, melt flow rate and oxidative induction time. For both resins the same spray-on-process at high temperature and air pressure was applied, i.e. a smooth GM at room temperature was slowly moved below a crosswise operating spray gun.

Four different types of GCLs reinforced by needle-punching and manufactured exclusively for these tests, were studied. The cover and carrier geotextiles were made of high-density polyethylene (GCL 1) or polypropylene (GCL 2). Two different manufacturing methods were used in each case. Method A results in an enhancement of the anchor of the reinforcing fibres in the carrier geotextile compared to method B. Accordingly the samples are named GCL 1A and GCL 1B and GCL 2A and GCL 2B.

3.2 *Sensitivity of long-term shear strength to materials choice and manufacturing*

In the following we want to point out three general findings from experiences and results of long-term shear tests. Firstly, the test results of various products showed clearly that performance is substantially dependent on the materials, design and fabrication technique used to make the product.

Figure 6 shows the cumulative frequency of times to failure for GMs textured with resin A, which were tested at 80 °C against PP geotextiles under a vertical load of 50 kN/m². The time to failure data exhibits a logarithmic normal distribution, as expected in long-term testing of this type. The average time to failure however is only 2 days.

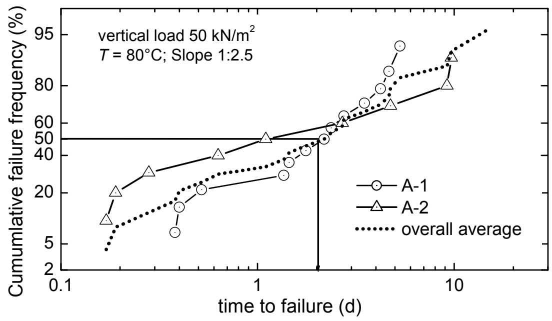

Figure 6 Cumulative frequency distribution of all times to failure (days) determined for textured GM A

Table 1 Times to failure (days) of the specimen from three samples of textured GM B

Sample number	B-3	B-4	B-259*
Times to failure (d)	> 395 > 395 399§ 404§	> 698 > 620 350§	> 396 > 524 > 524

§) Textured GM did not fail; geotextile separated from its fixing mount due to brittleness.
*) After 1500 hours of artificial weathering in accordance with DIN EN 12224.

Table 1 shows the times to failure of GM samples textured with resin B. Although subjected to the exact same fabrication and test conditions, this product exhibits much better performance in the test. In most instances this product completed test durations at 80 °C of over 1.5 years without failure. Slippage, if encountered at all, occurred after long test durations due to embrittlement of the geotextile, causing separation from its fixing mount on the wedge. Slippage due to failure of the texturing was not observed. Even 1500 hours of artificial weathering exposure (roughly equivalent to 2 years of outdoor weathering) prior to testing did not appreciably reduce time to failure in the subsequent long-term shear test of these samples.

During the spray-on-process a drastic degradation of the sprayed resins occurs. To date it is still unclear which minor variations in resin properties and the fabrication may cause such large differences in the times to failure.

There is another remarkable example for the fact that differences in materials may cause large differences in the times to failure. In Figure 7 and Figure 8 a polypropylene-GCL is compared to a polyethylene-GCL. When tested under identical test conditions the times to failure differ drastically, at least by one order of magnitude.

Different manufacturing processes might lead to different failure behaviour, which is not seen in short term peel tests, however, is of importance for the long-term behaviour. The failure of GCL samples A is accompanied by breaking of the reinforcing fibres from their anchoring within the carrier geotextile. On the other hand the reinforcing fibre bundles of GSL samples B were disentangled and pulled out of the carrier geotextile. Figure 7 and Figure 8 show the Arrhenius plot of the failure times versus temperature. GCL 1A failed much faster than GCL 1B under all testing conditions and GCL 2A failed much faster then GCL 2B, when tested in deionised water. With increasing temperature the times to failure decrease showing clearly an Arrhenius type of behaviour for samples A. The failure times at the chosen test conditions are so short that embrittlement due to oxidative degradation of the fibres is not relevant. However, the fibre breaking mechanism is accelerated by mixing surfactants into the water bath.

3.3 *Short-term versus long-term shear strength*

Our testing also established - an expected second general finding - drastic differences between short-term shear strength and long-term shear strength. For instance, the difference between textured GMs A and B referred to earlier was not observed in short-term friction testing.

Table 2 Peel strength in short-term testing and time to failure in long-term testing for different GCL products. To facilitate comparison, all data are expressed as relative values, i.e. multiples of the smallest value in each data group

Product number	Relative peel strength	Relative time to failure
GCL 1A	3,6	1
GCL 1B	3,3	4,4
GCL 2A	2	24
GCL 2B	1	>270

GCLs as well exhibit this difference between short-term and long-term behaviour. The short-term shear strength of GCLs is expressed as the maximum shear force (shear strength) or maximum peeling force (peel strength) observed in short-term shear or peel testing. Their long-term shear strength can be characterized by the shear stress withstood by 95 % of the samples tested over a given test duration at a specified temperature. It can also be characterized by the geometric mean of time to failure in long-term shear testing at specified shear stress and temperature. Table 2 below compares mean relative peel strengths and mean relative times to failure for different GCLs. The data clearly shows that high short-term strength does not necessarily indicate high times to failure under long-term stress. Long-term shear testing is therefore essential in evaluation of geosynthetics consisting of several structural or material components.

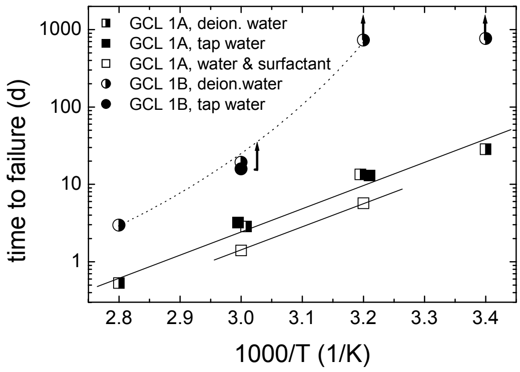

Figure 7 Arrhenius diagram of shear test results for GCL 1A and 1B. Temperature dependence of times to failure of samples 1A, where fibre rupture is found as failure mode, clearly follow an Arrhenius law. Surfactants influence the failure behaviour: the times to failure are reduced for water with added surfactant. In contrast, samples 1B reveal considerable larger times to failure which strongly deviate from a linear dependence on the inverse temperature. These specimen fail due to disentanglement of fibres. Arrows indicate mean elapsed times in tests still running

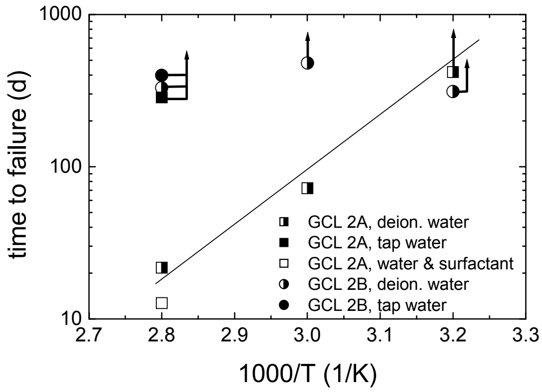

Figure 8 Arrhenius diagram of shear test results for GCL 2A and 2B. As with product GCL 1A, the temperature dependence of times to failure for samples 2A also follows an Arrhenius law and fibre rupture is found as failure mode, when tested in deionised water. Surfactants influence the failure behaviour in the same way as for sample 1A. Up to date no failures occurred for samples 2B, neither in deionised water nor in tap water. The same holds for samples 2A when tested in tap water. Arrows indicate mean elapsed times in tests still running

3.4 *Sensitivity of long-term shear strength to test conditions*

It is a third general finding established in our testing that the behaviour of geosynthetics in long-term testing is not easily predictable: Minor changes in test conditions can significantly affect test results. For instance, using tap water instead of deionised water as the testing environment for the GCL, it was found to substantially influence time to failure of samples GCL 2A (Figure 8). Ion exchange with the test environment alters the composition of the bentonite, significantly changing shear behaviour.

Still under investigation is the influence of various friction partners and of the variation of the loading condition on times to failure and failure modes.

When interpreting these laboratory results, it should be noted that the test conditions are highly demanding - e.g. high temperatures and continuous submersion in water - and selected with the specific purpose of accelerating failure. Service lifetimes under field conditions extrapolated from such data therefore inherently contain a substantial margin of safety.

4 CONCLUSIONS

Among the important findings established in our testing, one key fact stands out: Geosynthetic products, when fabricated from high-quality materials and optimally designed, can withstand extremely long test durations under the most demanding conditions. One example of this is provided by post-fabrication textured GM B, as was previously discussed (Table 1). Figure 8 shows a further example from long-term shear testing of GCLs. All GCL 2B product test specimens exhibit stable stationary creep, even after a mean test duration of almost one year at 80 °C, with no signs whatsoever of imminent failure. The same holds true for sample GCL 2A when tested in tap water.

Cap liners for landfills and contaminated industrial sites must provide very long service lifetimes and normally cannot be inspected or repaired. Therefore the suitability of geosynthetic products used in such applications must be documented by appropriate testing, particularly in the area of long-term performance. In Germany, this is specified by legal regulations (Technical Directive Municipal Waste in conjunction with the Waste Disposal Ordinance), which require documentation of equivalence of durability to CCL/HDPE-GM composite liner systems. The Landfill Ordinance now provides for the possibility of using GCDs in landfill cap liner systems. Footnote 4 in the liner system tables given in the Ordinance appendix 1 however also specifies: "The approving authority can authorize deviations from the specified layer thickness and permeability coefficient of the drainage layer upon request of the landfill operator if the hydraulic conduction capacity of the drainage layer and the sliding stability of the topsoil layer have been documented as being sufficient on a long-term basis." Geosynthetic manufacturers and distributors have to deal with these regulatory constraints.

GMs used to line landfills and contaminated industrial sites in Germany must be certified by BAM. Long-term shear strength testing of textured GMs is part of the certification procedure.

The suitability of GCLs used in these applications can be evaluated using the former certification requirements of DIBt (federal and states authority for constructions and buildings) as a general guideline, updated in accordance with current technological practice. GCL certifications issued by DIBt contained the proviso that supplementary proof of long-term shear strength was required. This proof can be effected by the test procedure presented in this paper.

Proof of suitability of GCDs can be effected on the basis of DIN EN 13252:2001-04, Geotextiles and Related Products, Required Properties for Applications in Drainage Layers. However the durability requirements specified in this standard explicitly provide for a service lifetime of only 25 years. Also the standard does not call for testing of long-term behaviour and drainage performance under simultaneous compressive and shear stress. Therefore, certification by this standard establishes suitability only for simple geotechnical applications, in which GCDs are accessible, i.e. can be repaired or replaced without prohibitive expense. GCDs used in landfill construction or containment of contaminated sites must be tested and evaluated for additional essential properties, i.e. long-term shear strength and long-term drainage performance, by procedures which take into account the ageing processes exhibited by the materials used. This testing can also be carried out on the long-term shear test apparatus presented here.

For correctly installed BAM-certified HDPE GMs, proof has been furnished that expected service life is on the order of centuries (Mueller 2003). For some GCL products, initial results for proof of long-term shear strength are now available (Figure 8). In the GCD sector, testing has begun and a guideline for the testing of such products for capping systems was issued by the BAM (Müller 2002a, 2002b). We hope that many manufacturers of geosynthetic products will participate actively in these test programs in the future. This is essential to provide a comprehensive overview on performance of multilayered geosynthetic products used over extremely long service lives under permanent and combined action of pressure and shear load.

5 ACKNOWLEDGEMENT

The results presented originated from BAM research projects, which were supported with funding and technical input by GSE Lining Technology GmbH and Naue Fasertechnik GmbH & Co. KG.

6 REFERENCES

Blümel, W., Brummermann, K., 1994: Reibung zwischen Geokunststoffen und Erdstoffen in Deponiedichtungen. Müll und Abfall 26(5), 242-259

Mueller, W. W., Jakob, I., 2003: Oxidative resistance of high-density polyethylene geomembranes. Polymer Degradation and Stability 79(1), 161-171

Müller, W. W., 2001: Handbuch der PE-HD-Dichtungsbahnen in der Geotechnik. Birkhäuser Verlag, Basel

Müller, W. W., 2002a: Kunststoff-Dränmatten im Deponiebau Teil 1: Eigenschaften und Beurteilung. Bautechnik 79(3), 178-192

Müller, W. W., 2002b: Kunststoff-Dränmatten im Deponiebau Teil 2: Zur Bemessung. Bautechnik 79(4), 232-242

Seeger, S., Böhm, H., Söhring, G., Müller, W., 2000: Long term testing of geomembranes and geotextiles under shear stress. In: Cancelli, A., Cazzuffi, D. and Soccodato, C. (Eds.), Proceedings of the Second European Geosynthetics Conference. Pàtron Editore, Bologna, pp. 607-610

Seeger, S., Müller, W. W., 2001: Langzeitbeständigkeit strukturierter Dichtungsbahnen, BAM-Forschungsbericht 256. Wirtschaftsverlag NW, Verlag für neue Wissenschaft GmbH, Bremerhaven

Thies, M., Gerloff, C., Seeger, S., Müller, W. W., 2002: Long-term shear testing of geosynthetic clay liners. In: Zanzinger, H., Koerner, R. M. and Gartung, E. (Eds.), Clay Geosynthetic Barriers. A.A. Balkema Publishers, Lisse, The Netherlands, pp. 97-104

von Maubeuge, K. P., Luca, S. N., 2002: Peel and shear test comparison and geosynthetic clay liner shear strength correlation. In: Zanzinger, H., Koerner, R. M. and Gartung, E. (Eds.), Clay Geosynthetic Barriers. A.A. Balkema Publishers, Lisse, Netherlands, pp 105-110