Geosynthetic Clay Liners and long-term slope stability

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ABSTRACT

Geosynthetic clay liners (GCLs) are relatively thin composite materials combining bentonite clay and synthetics (usually geotextiles). GCLs have been employed by the waste industry for well over a decade now, and their level of usage is rapidly increasing both in the British Isles and world wide. In landfill facilities, GCLs are generally used to replace or augment compacted clay liners. Until recently, the decision to do so has primarily been based on the availability of clay material on site (i. e., economic considerations). However, the advantages in using a GCL over other sealing elements such as compacted clay are not only economic but technically based, and the economic benefits extend beyond the construction phase, as a thin GCL can increase the revenue earning potential of a facility. This paper will highlight the shear behaviour of GCLs and demonstrate their long-term stability.

INTRODUCTION

Geosynthetic Clay Liners (GCLs), also called bentonite liners, are industrially manufactured, whereby a set quantity of natural sodium bentonite is confined between two geotextiles (Fig. 1). The carrier layer is either a woven or a combination woven/nonwoven geotextile which allows for good anchorage of fibres. The geotextiles are then needle-punched together through the intermediate bentonite layer, securing the bentonite in place and reinforcing the otherwise weak layer of clay (when hydrated).

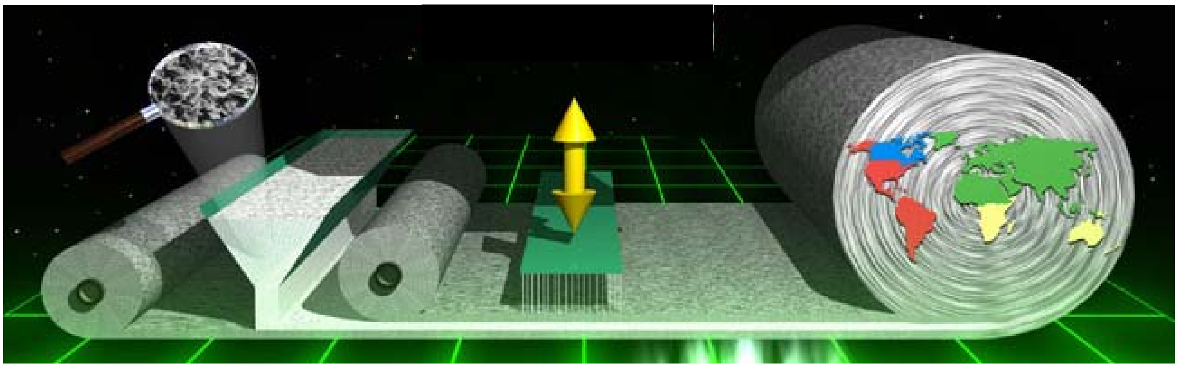

Figure 1: Schematic drawing of the manufacturing process of a needle-punched GCL

The low midplane friction angle of bentonite (in hydrated condition peak approx. 9°, residual about 4° to 5°) is overcome by direction independent needle-punching or partly by direction dependent stitch-bonding (Fig. 2) [1]. Geosynthetic Clay Liners achieve hydraulic conductivities in the range of approx. 1×10^{-11} m/s at high confining stresses. At low confining stresses hydraulic conductivities of $< 5 \times 10^{-11}$ m/s may be expected for needle-

punched products. Higher hydraulic conductivities may occur with other GCLs, depending on the type of manufacturing process (e. g. 9×10^{-11} m/s) [2].
The focus on hydraulic conductivity becomes less significant since all manufacturers mainly use natural sodium bentonite. "Polymer additives for bentonite" is no longer a relevant topic since the long-term efficiency could not be proven in practice. Egloffstein [3] has questioned the long-term effects and has proven that the amounts of polymer had to be much higher than the amount of bentonite used (approx. 4 – 5 kg/m²) to ensure a long-term efficiency. The Environment Agency are currently drafting guidelines for the use of GCLs and are taking the position that the use of polymers is not to be encouraged. More important is the question of the long-term shear strength transfer.

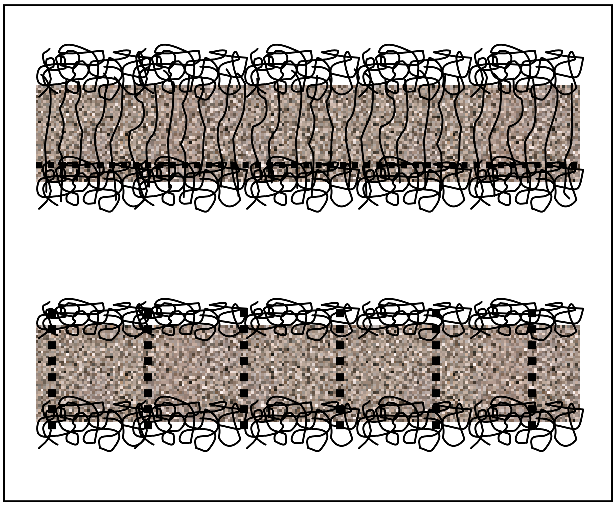

Fig. 2: Schematic cross-section of a needle-punched GCL (top) and a stitch-bonded GCL (bottom).

THEORETICAL BACKGROUND

Heerten et al. [4] published a theoretical approach which describes the shear behaviour for needle-punched GCLs, and a design diagram that shows the conditions under which the critical shear plane is not midplane but at the GCL interface (fig. 3). The main parameters are the confining stress, the slope inclination, and the GCL peel strength. The peel strength is an index parameter (von Maubeuge et al. [15]) where one geotextile layer of the GCL is fixed in the upper clamp and one in the lower clamp of the tensile force testing machine and the needle-punching which holds the GCL together is pulled apart. The peel strength achieved is reported in N/10 cm and is brought into relation to the normal stress and to the slope inclination (fig. 3). This design basis could be considered conservative as the needle-punched GCLs tested were pre-hydrated for 24 hours without any confining stress and the cohesion intercept determined was not taken into consideration.

A 24-hour-hydration was selected as according to the installation instructions for GCLs, a cover soil should be placed within 24 hours after deployment [13]. Heyer et al. [12] further propose that GCLs with a moisture content prior to covering of more than 50 % should be replaced, as the risk of bentonite thinning of the GCL after placement rises with an increasing moisture content.

The shear plane is assumed to be outside the needle-punched GCL if the determined value in the chart (fig. 2) lies above the chosen slope inclination; thus e. g. a slope inclination of 1.5 (h) : 1(v) could be achieved at a peel strength of 69 N/10 cm and a cover thickness of 4 m provided that the interface friction angles as well as the midplane friction angles of the adjacent layers achieve at least the same value. At a peel strength of 29 N/10 cm and 1.5 m cover, a slope with an inclination of approx. 33° is possible (fig. 3) but with 10 N/ 10 cm a internal failure would occur.

One commercially available needle-punched GCL has, according to von Maubeuge [6], approx. 2.5 million fibres per m² with a minimum strength of 40 cN per fibre. The result of this is the theoretical short-term shear strength of 1,000 kN/m² assuming that all fibres are locked and tear at the same time. In the shear test, however, lower shear strengths (load dependent) than the theoretical 1,000 kN/m² are achieved (fig. 3) so that it can be concluded – as recognised in the shear tests - that not the tearing of the fibre, but the pull-out resistance is relevant.

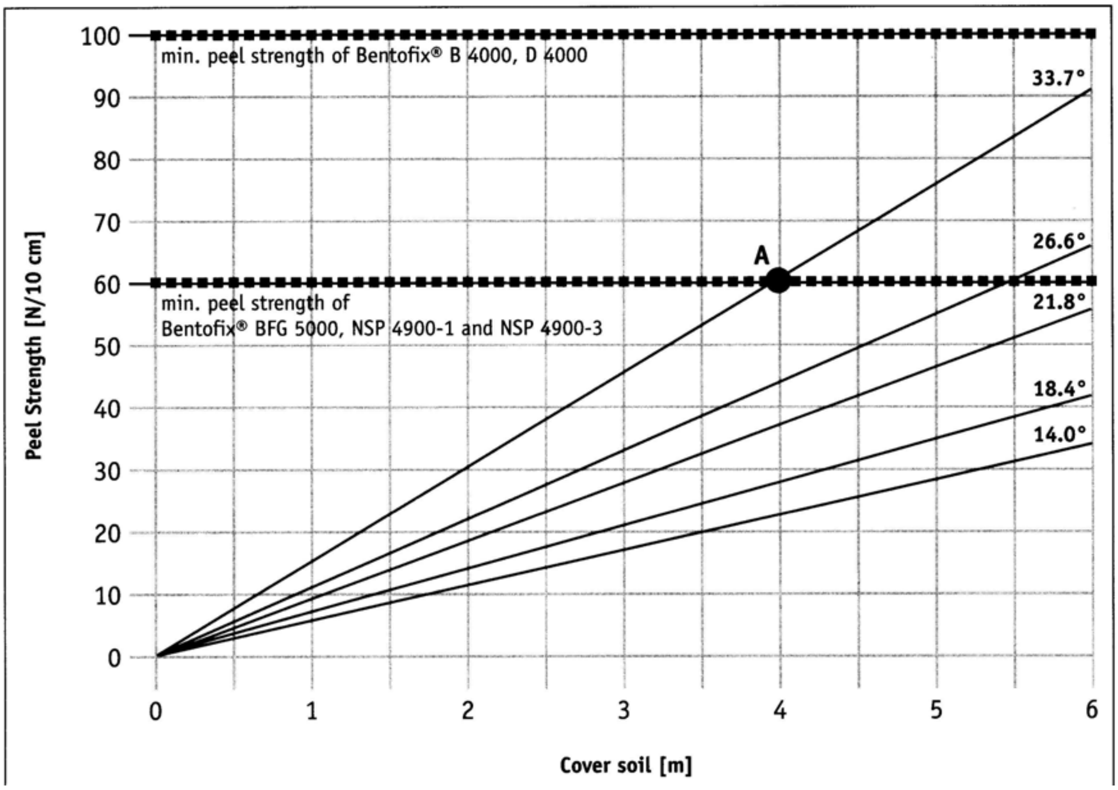

Fig. 3: Design diagram for the determination of the max. permissible slope angle as a function of cover soil ($\gamma = 20$ kN/m³) and GCL peel strength. If the point lies above the line, the GCL should not fail internally. Shear tests are required with typical soils from the site.

Once the fibres are activated in the field by the shear transfer of the actual load, a long-term pull-out (sometimes referred to as pull-out creep) is not of concern because the 2.5 million needle-punched fibres are not just simply anchored. Due to their crimped shape they are curled together three-dimensionally like knots. The staple fibres are also thermally fixed and this acts to prevent releasing of the knots. Thus a long-term pull-out of the anchored fibres is not to be expected and has been proven in long-term tests.

Due to the above theoretical work and testing it is now becoming common for quality control and on-site acceptance testing using the peel bond test procedure. To avoid fibre entanglement around the clamps it is recommended to use wide width clamps (ASTM 4595 or DIN EN ISO 10319). This clamping method is also anchored in the latest peel bonding test method ASTM D6496 “Test Method for Bonding Peel Strength of Needlepunched GCLs”.

In the past the peel bond test was specified occasionally but sometimes the specification just asked for a peel value without any further description. The latest ASTM D6496 test method for the determination of the peel bond strength of needlepunched GCLs, clearly specifies all the relative information.

These are:

Clamping method	As ASTM 4595 or BS EN ISO 10319
Specimen size	100 mm x 200 mm
Separation speed	300 mm/min
Readings	From 25 mm to 125 mm separation
Peel direction	In production direction
Single report value	Average
Report value	Average of five single values
Report unit	N/m

GENERAL SHEAR BEHAVIOUR OF GCLs

In order to examine the general shear behaviour of geosynthetic clay liners in hydrated condition, tests with different GCL types were conducted in the laboratories of Naue Fasertechnik GmbH & Co. KG, Germany. On an automatic tilt-table (1 m x 1 m) a textured geomembrane (GM) was fixed upon which each GCL type was placed. After 24 hours of free hydration (horizontal position) again a textured geomembrane was placed on the hydrated GCL. The setup was then loaded with a 30 cm thick gravel layer (approx. 6 kN/m^2). The box was constructed in such a way that the shear plane could only occur between one of the geomembranes and the GCL or in the GCL itself. After a consolidation (short term) time of 0.5 hours, the tilt-table was raised at a speed of 1°/min. Some representative results from the conducted tests are shown in Table 1.

Table 1: Tilt-table resultss for the determination of the general shear behaviour of GCL types

#	Structure	shear plane	shear angle
1	5 kg bentonite between two geotextiles without additional reinforcement	bentonite	8°
2	5 kg bentonite between two geotextiles, fixed with water-soluble glue	bentonite	8°
3	4.5 kg bentonite between two geotextiles, needle-punched with 8 N/10 cm peel strength	bentonite	18°
4	4.5 kg bentonite, stitch-bonded between two nonwovens (200 g/m^2)	between upper GM and GCL	29°
5	4.5 kg bentonite between two nonwovens 300 g/m^2, needle-punched with a peel strength of 30 N/10 cm	between upper GM and GCL	33°
6	4.5 kg bentonite between a 200 g/m^2 nonwoven and a 100 g/m^2 woven, needle-punched with a peel strength of 65 N/10 cm	between GM and woven of GCL	22°

The conducted tests highlight two significant factors in the behaviour of GCLs:

a) The peel strength between the single geotextile layers has a decisive influence on the shear behaviour of GCLs. The results are in agreement with the design diagram (fig. 3).

b) At a sufficient midplane shear force transfer the selection of the adjacent geosynthetics is significant for interface shear. Light needlepunched nonwovens (~ 200 g/m^2) and wovens show lower shear angles than thicker needlepunched nonwovens (~ 300 g/m^2).

In addition, mechanically bonded nonwovens with a higher mass per unit area (~ 300 g/m²) provide a better protection for the encapsulated bentonite and thus are more resistant against construction conditions than thinner geotextile components.

Upon selecting a GCL, particularly needle-punched GCLs, not only the reinforcing (midplane) shear strength is relevant. Interface shear behaviour (interface friction angle) is just as important. Nonwovens achieve higher shear values against adjacent soils than wovens, due to the three-dimensional structure. Without considering the influence of possible extruding bentonite (see [7] or section "Large-Scale Test Plots"), the following relationships (tanφ' / tanψ') for interface friction angles of geotextiles can be assumed according to Grett [11] (ψ' = soil friction angle, φ' = interface friction angle of soil / geotextile):

	needle-punched nonwoven	**woven**
clay	**~ 0.92**	**~ 0.84**
fine sand	**~ 0.92**	**~ 0.80**
coarse sand	**~ 0.95**	**~ 0.83**

LONG-TERM SHEAR BEHAVIOUR

In order to prove the design diagram (fig. 3) and the long-term durability of the fibre composite as function of the peel strength, Naue Fasertechnik GmbH & Co. KG constructed long-term shear boxes and examined the long-term shear behaviour and possible creep deformations on Bentofix type B (300 g/m² needle-punched cover nonwoven – 3500 g/m² natural sodium bentonite powder – 350 g/m² woven-reinforced needle-punched nonwoven).

Fig. 4: Long-term shear boxes with Bentofix® type B

On slope inclinations of 2.1 : 1 (25°) the GCL was covered with crushed gravel (2/8 mm) in a thickness of 30 cm (approx. 6 kN/m²) and the gravel was loaded with steel plates (25 kN/m²). In order to keep the bentonite permanently hydrated, a watering device was installed that waters the GCL daily with 10 litres water. Only the bottom (carrier) geotextile was fixed at the upper edge of the long-term shear box. This ensures that the shear force is actually transferred by the fibre reinforcement. A displacement of the upper geotextile to the lower geotextile layer could be observed at the edges during the entire testing period.

In the first test, a needle-punched GCL with a peel strength of only 10 N/10 cm was selected. It can be seen from fig. 3 that a sliding within the GCL had to be expected since the minimum peel strength of the GCL at a normal stress of 31 kN/m² (approx. 1.5 m cover) and at a slope inclination of 2.1:1 should have been at least 18 N/10 cm.

In the first 10 days a displacement of approx. 2 cm between the upper and the lower geotextile layer occurred. After 23 days a midplane slide – as anticipated - occurred. It was recognised that the anchoring fibres had been pulled out of the lower geotextile layer.

In a second test, a needle-punched GCL with a peel strength of 29 N/10 cm was selected. According to fig. 3 with this peel strength on a slope inclination of 2.1:1 a normal stress of approx. 52 kN/m² (approx. 2.5 m soil) could be safely applied without having to expect that the shear plane would occur within the GCL.

This set-up was installed on October 3, 1993. As in the first test, a displacement of 2 cm of the upper to the lower geotextile layer occurred after 2 days. Since that time no further displacement has been encountered, not even after more than 58,000 hours (6 ½ years on June 3, 2000).

The design diagram was verified in the long-term test as well as the fact that a detectable creeping or pulling out of the needle-punched fibres did not occur.

CREEPING

Since all geosynthetics tend to creep (longitudinal movement under permanent load), a safety factor is used for designs using geosynthetic reinforcement. Normally this value is supposed to be 4 so that the possibility of creeping of the Bentofix® fibre reinforcement would only occur at > 250 kN/m² according to the theoretical approach of section "Theoretical Background". Hewitt et al [5] carried out various shear tests with GCLs and it was recognised that such shear stresses occurred in needle-punched GCLs at normal stresses of > 400 kN/m² (approx. 20 m cover). However, creep testing was carried out on Bentofix® GCLs [8] even though such high shear stresses are rarely expected in GCLs (e.g. in piggy-back landfills, high dam constructions)

In shear boxes with a size of 30 cm x 30 cm (lower box 30 cm x 35 cm) the creep behaviour of the Bentofix® types B 4000 (NW) and NSP 4900 (NS) was examined. The saturation, consolidation, and shear stages were carried out with loads upto 630 kN/m².

After applying 50 % of the normal stress as creep stress (shear stress) no significant displacements between the cover nonwoven and the carrier geotextile had been recognised – at low normal stresses (21 kN/m²) as well as at high normal stresses (630 kN/m²). The duration of each test was > 500 hours.

Thus the long-term shear tests in the 1 m x 1 m boxes were not only confirmed for low normal stresses, but also for normal stresses of up to 630 kN/m²; a subject matter which may be relevant for intermediate sealings and base sealings where shear stresses in this range have to be transferred.

LARGE-SCALE TEST PLOTS

In 1994 the US American Environmental Protection Agency (EPA) initiated large shear tests in Cincinnati to verify the midplane shear strength of GCLs. These tests were supervised by the University of Texas at Austin, Geosynthetic Research Institute in Philadelphia and Geosyntec Consultants in Atlanta. For the first time the results were presented by Koerner [9] on the VDI (Association of German Civil Engineers) seminar in Karlsruhe on October 9 and 10, 1996. Latest results were presented at the Geo-Bento conference in Paris [10].

The aim was to prove that the midplane friction angle of GCLs is sufficiently high on slopes (length between 30 m and 20 m) with inclinations between 3:1 and 2:1 so that it may be assumed that a safety of 1.5 is given on slopes with an inclination of 3:1.

The GCLs were installed in November 1994 on a subgrade of silty sand and were covered with a 1.5 mm thick textured geomembrane, a geonet composite (with mechanically bonded nonwoven on both sides) and a 1 m thick soil layer. To avoid passive forces, a toe support was not installed. After one and two months the first two slides occurred on the 2:1 slopes. In both cases the failure surface was the woven side of the GCL against the geomembrane. Afterwards it was discovered that the interfacial friction angles from shear tests had values between 20° and 23° and more, thus significantly lower than the actual slope inclination. Additionally it was found that bentonite had partly extruded from the woven side and further decreased the interface friction between geoemembrane and woven. This bentonite extruding has been reported for thin mechanically bonded (< 220 g/m²) nonwovens by Gilbert [7]:

"Second, for GCLs with bentonite encased between geotextiles, the bentonite may extrude through the geotextiles into adjacent interfaces and affect the interface strength. Bentonite extrusion is normally associated with woven geotextiles, although it has been observed for thin (i. e. mass per unit area less than 220 g/m²) nonwoven as well."

Meanwhile Koerner [10] reported that plot F had an internal failure. Bentonite between two geomembranes hydrated and the wet bentonite sheared as it was not reinforced.

The peel strength of the two needle-punched GCLs in the plots which did not fail was tested > 90 N/10 cm and thus they remained stable. According to Fig. 3 at least 6 m of cover soil can be transmitted with this peel value.

In the meantime deformation has been recognised in the plots I, J. K, and L due to occurring subsoil failure. Koerner [10] reported: ".. *the general indication was that the entire lower half of these four test plots were deforming within the subgrade soils beneath the GCLs."*

A conclusion after the test trial is:

- needle-punched nonwovens give a better interface friction contact than wovens
- bentonite can extrude through wovens and nonwovens (≤ 200 g/m²)
- thicker (> 270 g/m²) nonwovens are safer solutions for GCLs due to better interface contact and bentonite retention in the GCL
- needle-punched nonwovens should be on both sides of the GCL where shear stress is applied to the GCL.

GLOBAL TRENDS

As a result of the type of work carried out above and the importance of long term slope stability and the confidence that must be placed in the materials used, needle-punched shear transferring GCLs account for the majority of world wide sales.

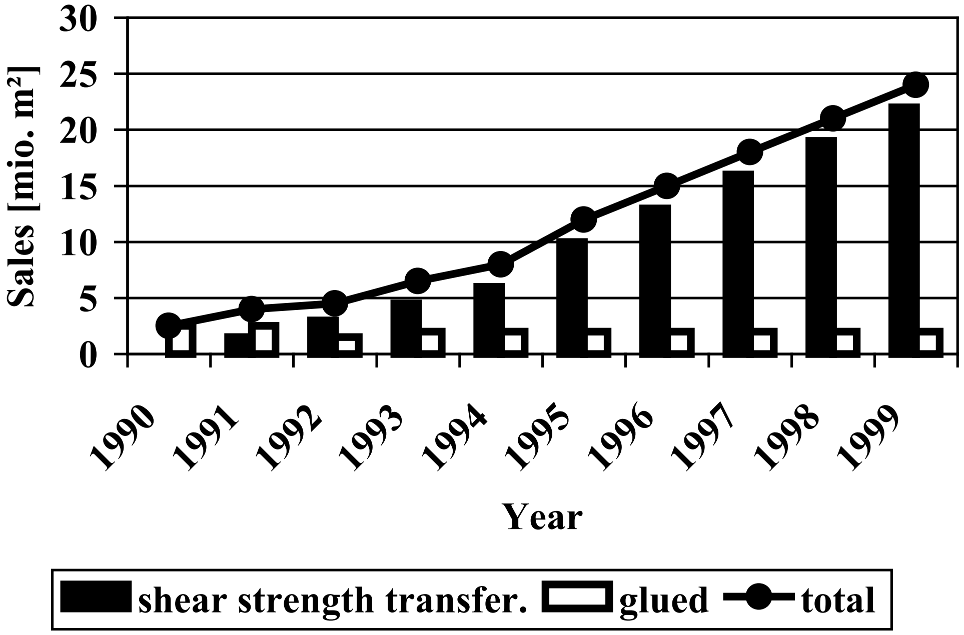

Fig. 5: Estimated GCL sales world-wide

SUMMARY

Needle-punched geosynthetic clay liners show a lot of technical advantages. Beside the low hydraulic conductivity, the self-sealing capability, and the elongation capability, the shear strength is an important criterion for the long-term efficiency of this product group.

The requirement for a minimum peel strength is necessary for steep slope applications. It is important that the proof of long-term stability is conducted by means of field studies. In order to achieve an interface friction angle as high as possible against the adjacent interfaces (e. g. textured geomembrane or soil), mechanically bonded nonwovens are especially suited. With a mass per unit area > 220 g/m² not only a good bond is achieved, but also a possible extrusion of bentonite is prevented.

Also, substantial costs can be saved by using geosynthetic clay liners. This cost-saving sealing layer can be installed more easily and faster and thus also more economically than compacted clay liners, capillary barriers or concrete sealings.

The existing examinations on the long-term performance exactly show that needle-punched geosynthetic clay liners are a predictable and long-term stable sealing element.

It is important that as the United Kingdom uses more and more of these materials that designs are carried out properly and that

- ◆ the shear transferring properties
- ◆ as well as the peel bonding strength of the GCL

are taken into consideration. The potential for creep particularly on landfill caps also needs to be addressed, whilst the specification for caps can be lower, the GCL must still perform adequately, ie that creep does not occur.

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