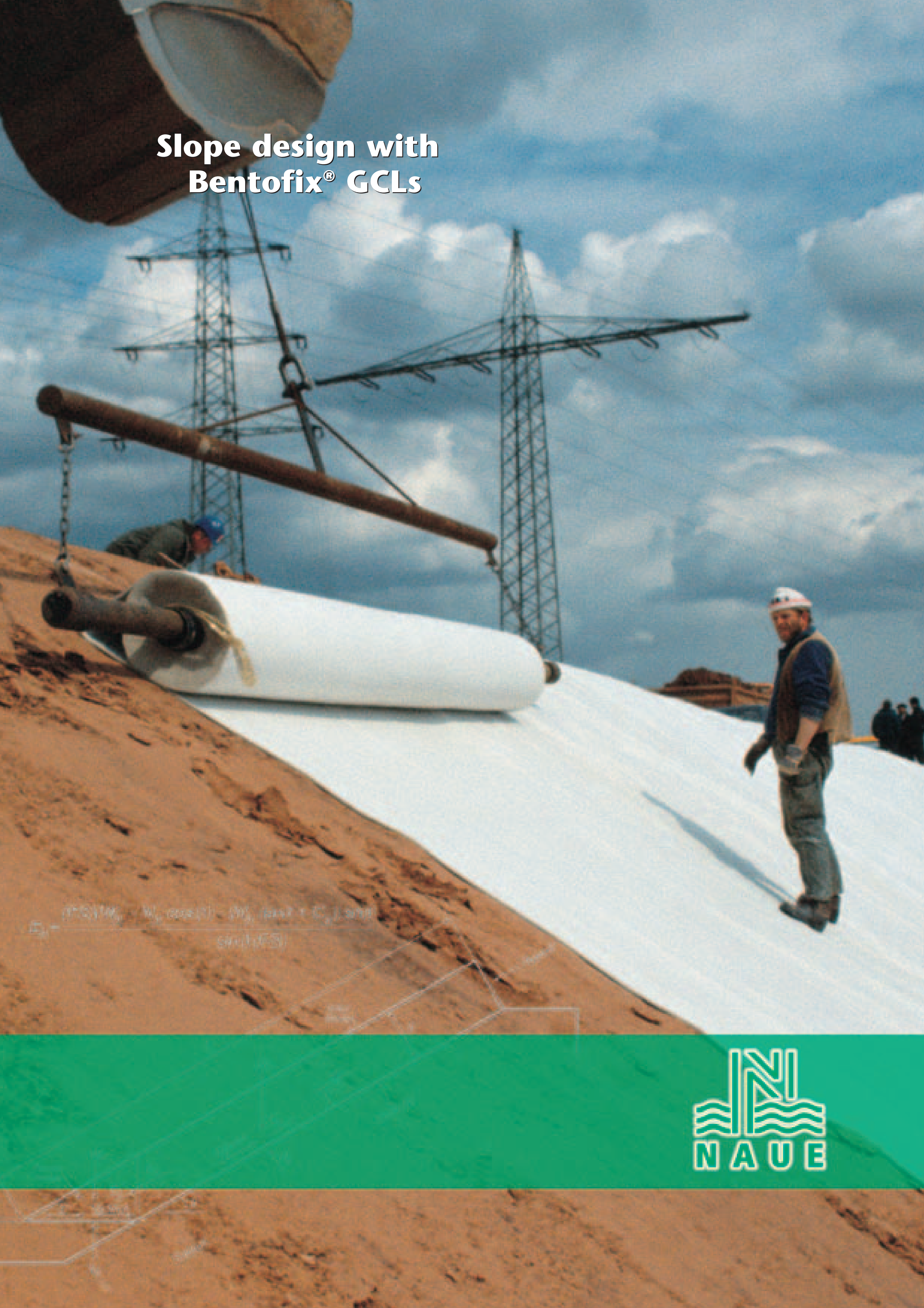
Slope design with Bentofix® GCLs



1. Introduction

Bentofix® geosynthetic clay liners (GCLs) are industrially manufactured composite materials combining high swelling bentonite clay and geosynthetics for sealing applications. The low hydrated midplane friction angle of the bentonite alone (peak approx. 9°, residual about 4° to 5°) is overcome by the needlepunching (Fig. 1) of all components creating a uniform shear stress transmitting GCL. Bentofix® GCLs have been employed world-wide for nearly two decades now. They are generally used to replace or augment compacted clay liners. The hydraulic conductivity is in the range of $\leq 5 \times 10^{-11}$ m/s. One main advantage of needle-punched GCLs is that they can be installed in steep slope applications (e.g.: Bentofix® on a 45 m long slope in a landfill cap application on a 2:1 (26.6°) slope). For such applications it is important to evaluate the interface shear stress of the GCL and prove that the internal shear stress of the GCL is sufficient to meet design criteria.

2. Theoretical background and design diagram

From theory, approximately 2.5 million fibres per m² reinforce the bentonite clay layer as they are needle-punched from the cover geotextile to the carrier geotextile.

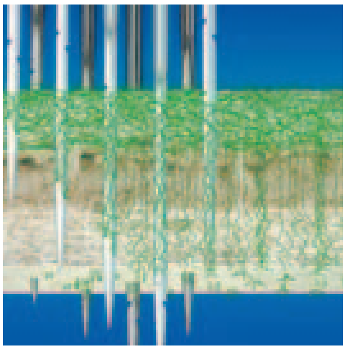


Figure 1
Schematic cross-section of a needle-punched Bentofix® GCL

The needle-punched fibres have a tensile strength of 40 cN so that the reinforcement can create a short-term shear stress of approx. 1,000 kN/m². Assuming the fibre reinforcement interlocks completely, a safety factor for polymer creep should be taken into consideration. Using a safety factor of 4, a theoretical long-term shear stress of 250 kN/m² is obtained.

In several hundred shear tests, the internal shear stress of Bentofix® GCLs was evaluated after a 24-hour-prehydration without confining stress to simulate worst case installation conditions or an underwater installation. The Bentofix® GCLs also varied in the quality control peel value so that the shear stress results could all be plotted against the peel value by converting shear stress into a confining stress (cover soil with a density of 20 kN/m³) and slope inclinations (Fig. 2). A cohesion intercept was not taken into consideration so that the obtained values are on the conservative side.

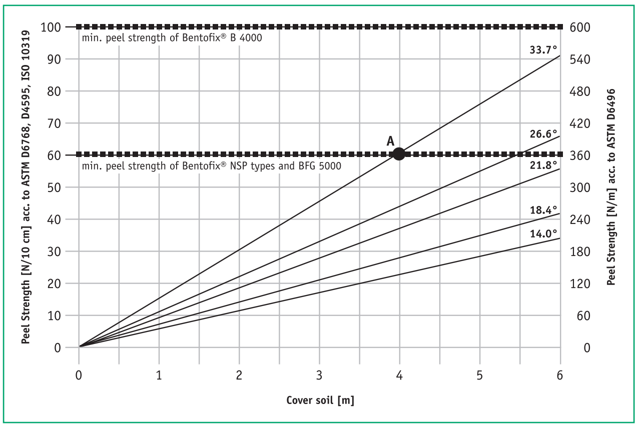


Figure 2
Bentofix® peel correlationship for design issues

It can be seen from figure 2 that a relationship exists between the peel value and the confining stress. The shear plane is outside of the Bentofix® GCL if the given peel strength value is above the chosen slope inclination for the selected cover soil depth. The value A in figure 2 indicates that no internal failure occurs for Bentofix® NSP 4900 on 1.5:1 (33,7°) slopes with a confining stress of 4 m cover soil (80 kN/m²) but could occur with 5 m cover soil.

It can be shown that the achieved manufacturing quality control (MQC) peel values for the Bentofix® GCLs satisfy the design needs for most low confining stress applications.

Figure 3
Automatic tilt-table and shear box

3. General shear behaviour of GCLs

To examine the general shear behaviour of GCLs in a hydrated condition, tests on different GCL types were conducted after 24 hours horizontal prehydration with no confining stress in the laboratories of NAUE GmbH & Co. KG, Germany. On an automatic tilt-table (1 m x 1 m), the GCLs were sheared between textured geomembranes (GM). The set-up (Fig. 3) was then loaded with a 30 cm thick gravel layer (approx. 6 kN/m²). 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 short-term consolidation time of 0.5 hours, the tilt-table was inclined at a rate of 1°/min. Some representative results from the conducted tests are shown in table 1.

Table 1
Results of the tilt-table tests for determination of the general shear behaviour of GCL types

Structure	shear plane	shear angle
5 kg bentonite between two geotextiles, fixed with water-soluble glue	internal	8°
4.5 kg bentonite between two geotextiles, needle-punched with 8 N/10 cm peel strength	internal	18°
4.5 kg bentonite between a 200 g/m² nonwoven and a 100 g/m² woven, needle-punched with a peel strength of 65 N/10 cm	external (woven)	22°
4.5 kg bentonite, stitch-bonded between two nonwovens (200 g/m²)	external	29°
4.5 kg bentonite between two nonwovens 300 g/m², needle-punched with a peel strength of 30 N/10 cm	external	33°

The test results highlight two significant factors in the behaviour of GCLs:

a) The peel strength of needle-punched GCLs has a decisive influence on the shear behaviour.

b) At a sufficient internal shear strength transfer, the selection of the adjacent geosynthetics is significant for interface shear transfer.

Light needle-punched nonwovens (~ 200 g/m²) and wovens show lower shear angles than thicker needle-punched nonwovens (~ 300 g/m²).

4. Examples of interface shear values

Upon selecting a GCL, not only is the reinforcing internal shear stress relevant but the interface shear behaviour is just as important. For a first assumption, the relationship ($\tan \varphi' / \tan \psi'$) for interface friction angles of geotextiles can be assumed according to Grett (φ' = interface friction angle of soil vs. geotextile, ψ' = soil friction angle), but cannot replace shear tests with site soils. Examples are shown in table 2.

Table 2
Assumed interface friction relationship of geotextile and soil

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

Direct shear test with on-site soils should follow as close as possible on-site conditions, including for example confining stress and hydration of GCL. Table 3 summarises the range of shear angles which have been achieved in various interface shear tests against geosynthetics and soils, and clearly show that the woven component of the GCL in general achieves lower friction angles than needle-punched nonwoven components of a GCL.

Table 3
Evaluated interface shear angles of GCLs geotextile components against geosynthetics or soils

adjacent geo-synthetic or soil	range of friction angle woven	nonwoven
smooth geomembrane	8° to 12°	8° to 12°
textured geomembrane	10° to 25°	18° to 35°
top soil	18° to 28°	21° to 32°
sand	21° to 28°	24° to 32°
sandy gravel	23° to 28°	25° to 34°

5. Long-term laboratory shear behaviour

In April of 1994, NAUE constructed several large-scale creep shear devices to evaluate the behaviour of NSP style needle-punched woven/nonwoven Bentofix® GCLs, under simulated in-situ conditions of low normal load applications. The testing program included the measurement of differential creep movement as well as additional post-test shear testing on the GCL material.

The material tested was the Bentofix® BFG 5000, a "sister product" product within the NSP series of Bentofix® GCLs (woven/nonwoven combination). To ensure applicability of this data to all NSP series needle-punched Bentofix® products, the specimen selected exhibited a peel strength at the lowest end of the strength spectrum.

The Bentofix® GCL being tested was mounted to a 1 m x 1 m test apparatus in the following cross section (top to bottom):

- 25 kN/m² steel plates
- 30 cm of 2 - 8 mm crushed gravel contained in a steel box
- Bentofix® GCL with carrier geotextile anchored to the bottom steel plate

Prior to the initiation of the test, the entire apparatus was gradually tilted to reflect a slope angle of 25° (2.14:1), resulting in a constant strain of 14 kN/m², under a confining stress of approx. 30 kN/m². To ensure thorough saturation, the sample was hydrated daily.

Testing was initiated on April 17, 1994 and continued until December 1, 1998 for a total lapsed time of over 40,800 hours.

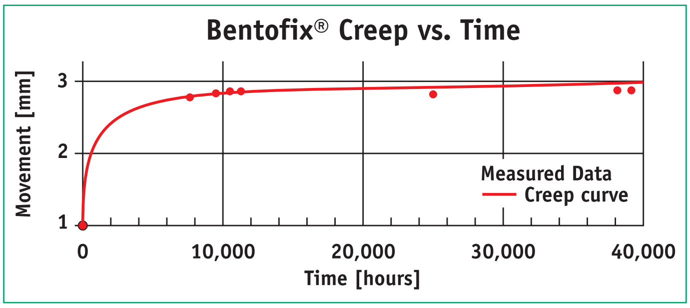
Upon the initial loading of the specimen with the confining stress, a small amount of movement was measured in the system, associated with the settling of gravel in the steel box. While movement occurred, it was not creep or elongation in the needle-punched GCL. Regardless, it has been included in the final displacement figures to ensure the most conservative picture.

With an initial value of 2.5 mm of movement, the final value shortly before dismantling the box was a total differential movement of 2.9 mm (includes the shifting) during the over 40,000 hour period (Fig. 4).

The Bentofix® GCL was tested for its peel and shear strength after dismantling the device to more fully evaluate the specimen. The minimum peel strength was still within certifiable limits for the standard Bentofix® NSP style material (greater than 60 N/10 cm). Three direct shear tests performed under full hydration and a normal load of 25 kPa showed a maximum shear stress of 64.8 kPa, 78.4 kPa and 84.1 kPa after over 40,800 hours of creep testing.

The Bentofix® NSP style GCLs, including the BFG 5000 and NSP 4900 products are not prone to creep distortion under conditions replicating low-load/low stress applications described herein. While the creep resistance of a material is directly related to the needle-punched fibres themselves, similar testing on other Bentofix® variations reflects the same conclusion, that the Bentofix® woven/nonwoven style GCLs are resistant to the long-term affects of constant strain under low normal loads. A second large-scale creep shear device with a Bentofix® nonwoven/nonwoven GCL is running under the same testing conditions since October 1993 with neither creep nor displacement being evident.

Figure 4
Creep behaviour of Bentofix® GCLs in correlation to time



6. Long-term field study

This long-term shear performance of needle-punched Bentofix® GCLs was also confirmed on the Cincinnati EPA slope stability study (Fig. 5), where, amongst other GCLs, Bentofix® GCLs were installed on 2:1 (26°), 30 m long slopes. The Bentofix® GCLs have not failed internally or interfacially. One non-reinforced GCL failed internally in the bentonite layer due to hydration of the bentonite. In two other slides, the cover soil, the drainage net, and the geomembrane overlaying the GCL slid at the weaker interface between the woven side of the GCL and the textured geomembrane. In direct shear tests it was determined that this interface only appeared to have a friction angle of approx. 20° to 24°, too low for a 2:1 slope. In slopes 3:1 (18,4°) or steeper, it is therefore recommended to use needle-punched GCLs with needle-punched nonwovens on both sides.

Figure 5
EPA field study on 2:1 slopes

Summary

Bentofix® needle-punched geosynthetic clay liners show many technical advantages. Besides the low hydraulic conductivity, the self-sealing capability and the elongation properties, the peel value and the shear strength are important criteria for the long-term efficiency of GCLs. The requirement for a minimum peel strength is necessary for every slope application. It is important that the proof of long-term stability is conducted. In order to achieve necessary interface friction angle against the adjacent interfaces (e. g. textured geomembrane or soil), mechanically bonded nonwovens are especially suited. With a mass per unit area of ≥ 200 g/m² good interface shear performance is achieved.

The existing examinations on the long-term performance of Bentofix® GCLs show that needle-punched Bentofix® geosynthetic clay liners are predictable sealing barriers and provide long-term stability.

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