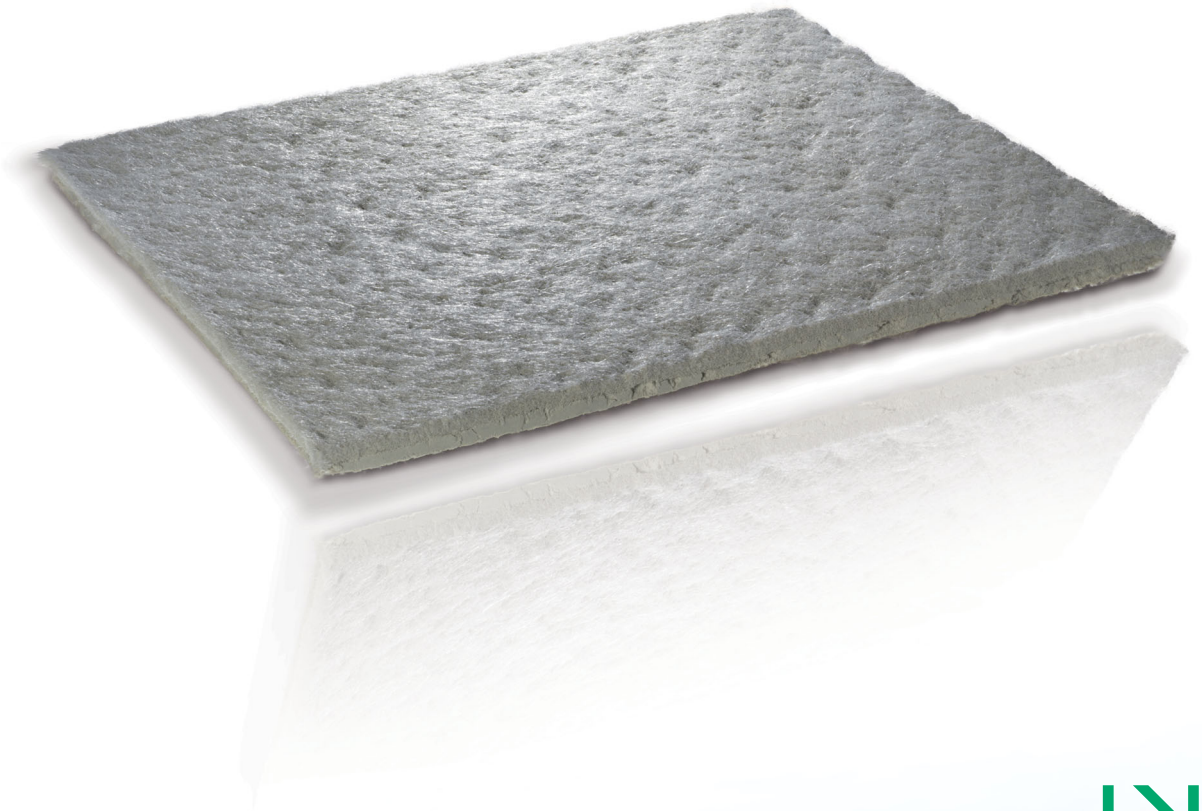
Bentofix® IQ

SMARTER ENGINEERING, BETTER BARRIERS

DESIGN MANUAL



The Inventor of
Needle-punched Geosynthetic
Clay Liners. Outstanding Quality
and Longest Experience.
Bentofix® - The Original!

NAUE

1 It's Called Bentofix®

Bentofix® Thermal Lock geosynthetic clay liners (GCLs) - also known as geosynthetic clay barriers (GBR-C) - are needle-punched, reinforced composites that combine two durable geotextile outer layers and a uniform core of high-swelling powder sodium bentonite clay. This construction forms a shear-resistant hydraulic barrier with self-sealing and re-healing characteristics. When hydrated with fresh water, the bentonite swells and forms a low permeability gel layer, the hydraulic performance of which is equal to or better than traditional, thick compacted clay liners.

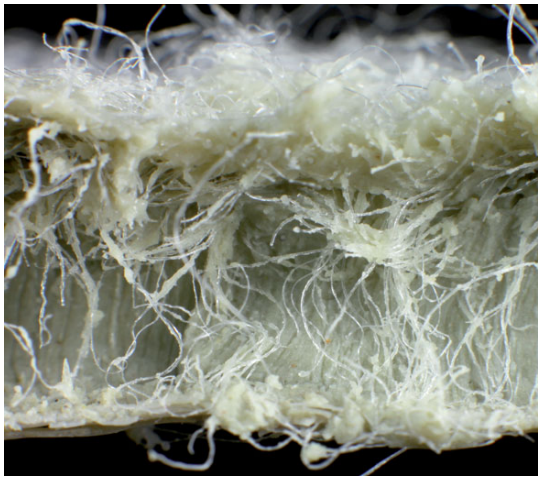


Figure 1
Bentofix® the original needle-punched geosynthetic clay liner

The composite construction of a geosynthetic clay liner (GCL) exemplifies how geosynthetics perform best: by interacting with natural elements to create something stronger or more secure. Bentofix® GCLs revolutionised the field more than 20 years ago with the invention of the needle-punched manufacturing technology that greatly increased the internal and external shear strength of GCLs and expanded the range of applications in which GCLs could be used. The needle-punching process firmly bonds the three unique layers of Bentofix® – two outer encapsulating geotextiles and the core of sodium bentonite. This bond creates a single, engineered barrier that utilises the best of both synthetic and natural materials.

Figure 2
Installed Bentofix® GCL for environmental protection under a road.

Together, these components outperform significantly thicker layers of compacted clay. The exceptional, immediate swelling characteristic of powdered sodium bentonite provides a long-term barrier that can "self-seal and re-heal" (e.g., swell to fill potential punctured/damaged zones) and rehydrate to renew the barrier even if it has been exposed to desiccation. The highly engineered geotextile outer layers provide outstanding protection against piping of the bentonite, durability to resist damage, and strength to manage the challenges inherent in barrier designs, such as for security on slopes and against fluctuating heads.

Some of the typical Bentofix® applications include:

- Canals, dams, dykes and levees
- Landfill caps, base liners, and slopes
- Environmental protection beneath roads and rails
- Noise barriers
- Secondary containment
- Industrial, mining, and decorative ponds
- Waterproofing
- Tunnels

Figure 3
Bentofix® GCL in a landfill cap under an HDPE Carbofol® geomembrane

Bentofix® Applications

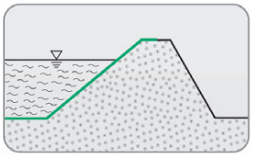
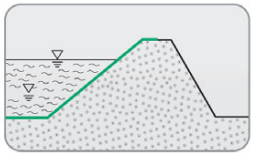
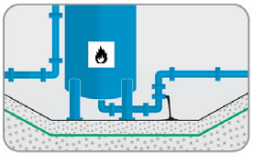
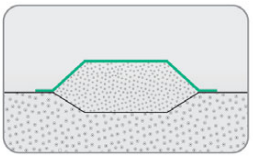
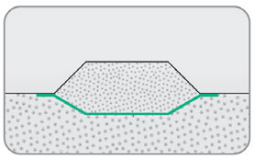
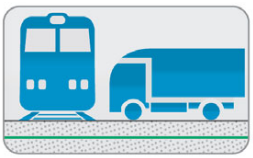
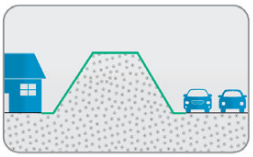
		Estimated design importance (1 - low; 10 very high) 1 2 3 4 5 6 7 8 9 10	Additional recommendations for Bentofix® X (with coating)
	Reservoirs, dams and canals (permanent water head)	Hydraulic water head Effect of chemicals Desiccation Root growth	Coating up Taping of overlaps typically not required
	Reservoirs, dams and dykes (variable water head)	Hydraulic water head Effect of chemicals Desiccation Root growth	Coating up Taping of overlaps typically not required
	Secondary containment, tankfarms	Hydraulic water head Effect of chemicals Desiccation Root growth	Coating up Taping of overlaps required
	Landfill Cap and closures	Hydraulic water head Effect of chemicals Desiccation Root growth	Coating up Taping of overlaps typically not required (only if gas is present)
	Landfill base liners	Hydraulic water head Effect of chemicals Desiccation Root growth	Coating up as single liner Taping of overlaps typically required Coating down as composite lining system Taping of overlaps typically not required
	Infrastructure constructions	Hydraulic water head Effect of chemicals Desiccation Root growth	Coating up Taping of overlaps typically not required
	Noise barriers, soil encapsulation	Hydraulic water head Effect of chemicals Desiccation Root growth	Coating up Taping of overlaps typically not required
	Waterproofing of underground structures, including tunnels	Hydraulic water head Effect of chemicals Desiccation Root growth	Coating not against concrete Taping of overlaps typically required

Figure 4
Recommended four selected design importance ratings (required for figure 17) for sealing applications with Bentofix® - other criteria may also apply according to importance.

2 Smarter Design: Thermal Lock

NAUE's innovations in GCL manufacturing and contributions to the understanding and adoption of GCLs in engineering and construction have been numerous. In addition to needle-punching, NAUE has created the proprietary heat-treating process Thermal Lock. This manufacturing technique permanently locks the needle-punched fibres of the nonwoven geotextile layer with the Bentofix® carrier layer and improves the hydraulic conductivity performance at low confining stresses. Thermal Lock increases the pullout resistance of the fibres - a durability-improving measure that increases interface friction, ensures long-term shear resistance and immediate fibre-strength during hydration.

Figure 5
Thermal Lock structure on Bentofix® GCL

3 The Next Phase for Bentofix® GCLs

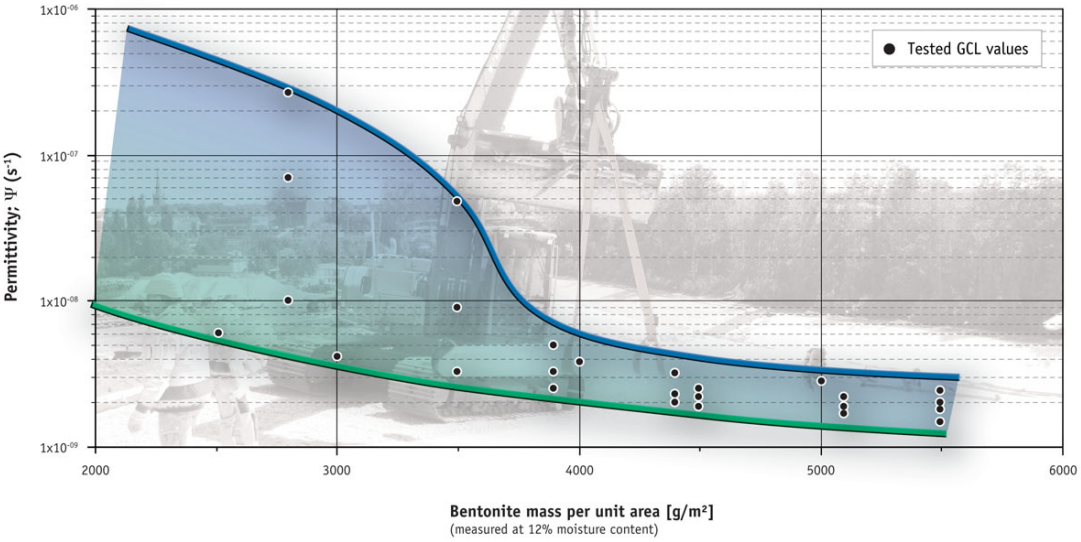
The strongly bonded geotextiles hold a GCL's bentonite layer in place and improve the composite material's durability and performance. The success of Bentofix® GCLs has been proven by millions of square metres of installed material. However, there might be situations where an improved GCL is the right choice, e.g. if gas can flow through in the first phase of an application if the bentonite is not yet hydrated; or desiccation can influence the performance of the GCL's bentonite layer. This is not an issue for every installation, but is for some, e.g. waterproofing in areas where radon gas occurs, applications with low confining stresses, or with ponds, lagoon, and canal applications. The most recent Bentofix® GCL development is a firmly attached polyolefin polymer coating - which exemplifies how modifications to GCL product design can be made to anticipate the special challenges of a particular site. Bentofix® X is the new needle-punched GCL type, to which the extruded polymer coating is attached to the woven side of the Bentofix® GCL, creating an additional low-permeability barrier prior to hydration. Bentofix® X is an advance for GCLs in some specific applications.

Figure 6
Attaching the extruded coating to the Bentofix® woven carrier layer

4 The Right Bentonite Mass Per Unit Area

The mass per unit area of the sodium bentonite in a geosynthetic clay liner is important to its hydraulic permittivity. Hydraulic permittivity decreases as the mass per unit area of a GCL's bentonite increases, and that means a better barrier. A higher design factor of safety is also associated with higher mass per unit bentonite layers. Standards commonly cite a minimum mass (at 0% moisture content) of 3,700g/m² (GRI, USA & GIGSA, SA). In Germany, 4,500g/m² is a common minimum (at 12% moisture content; resp. 4,000g/m² at 0% moisture content). Bentofix® can be produced with a bentonite mass per unit area up to 8,000g/m² if necessary; however, NAUE recommends that one follows worldwide standards with minimum 3,700g/m² bentonite mass per unit area. This mass, in combination with the exceptional swelling performance of powdered bentonite, makes Bentofix® a safe choice for long-term hydraulic barrier performance.

Figure 7
Permittivity range in correlation to sodium bentonite mass per unit area (influenced by e.g. bentonite type, homogeneity of bentonite distribution, type of bonding, bonding density)



Bentonite* mass per unit area [g/m²]	Index flux [10^{-9} (m³/m²)/s]	Permeation [l/m²/s]	Permeation [l/m²/day]	Permeation rate [%]	
2,500	5.5	5.5×10^{-6}	0.48	153	Permeation high
3,000	4.8	4.8×10^{-6}	0.41	133	
3,700	4.3	4.3×10^{-6}	0.37	119	Permeation low
4,000	4.1	4.1×10^{-6}	0.35	114	
4,670	3.6	3.6×10^{-6}	0.31	100	
5,000	3.3	3.3×10^{-6}	0.29	92	
5,300	3.1	3.1×10^{-6}	0.27	86	
5,600	2.6	2.6×10^{-6}	0.22	72	Permeation very low
5,700	2.3	2.3×10^{-6}	0.20	64	
7,000	2.0	2.0×10^{-6}	0.17	56	
8,000	1.5	1.5×10^{-6}	0.13	42	

*(12% moisture content)

Figure 8
Permeation rates of Bentofix® GCLs tested with a water head of 1.5m in correlation to bentonite mass per unit area

5 Why Peel Strength is Important

Because geosynthetic clay liners are composite materials, and the layers are designed to work together, the bond strength between GCL components is of particular interest. Already in 1994 NAUE technicians developed a key correlation between the standard peel test - which measures the strength between the carrier and cover geotextile - and the internal shear strength of the GCL. As peel strength increases, so does shear stress, which means that steeper or safer designs on slopes are possible. Even though the Bentofix® fibre reinforcement can hold the Bentofix® GCL composite under hydration together, it is recommended to add a confining stress of minimum 0.3m soil coverage over GCLs prior to any hydration. Bentofix® needle-punching increases the internal shear strength, ensuring a firm lock between the geotextile outer layers and the bentonite core. The needle-punching process and the locking of the needle-punched fibers with the Thermal Lock method additionally allows Bentofix® to exhibit a multidirectional, directionally independent, uniform shear and peel strength, which is important in many applications.

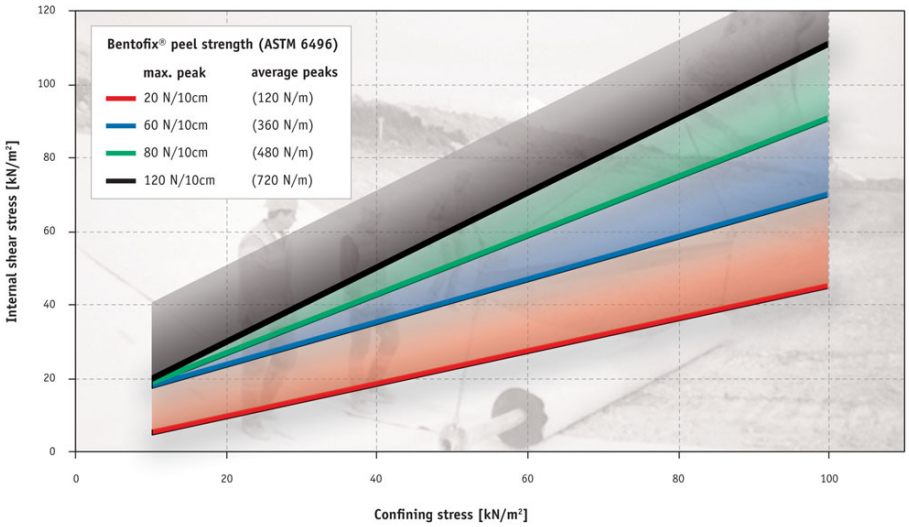
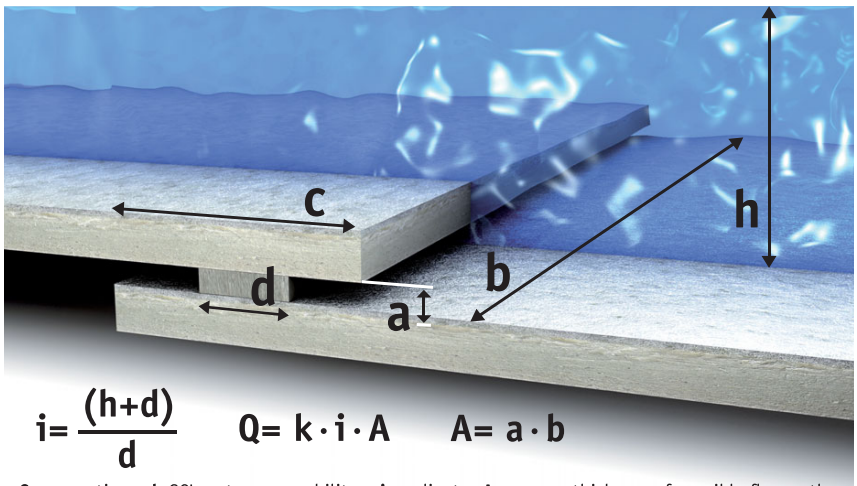


Figure 9 Conservative correlation of internal shear stress dependent on the Bentofix® peel strength (hydrated under low confining stress).

6 Safe Overlaps for GCLs



$$i = \frac{(h+d)}{d} \qquad Q = k \cdot i \cdot A \qquad A = a \cdot b$$

Q permeation · **k** GCL water permeability · **i** gradient · **A** area · **a** thickness of possible flow path in overlap · **b** overlap length · **h** water head · **d** bentonite width in overlap · **c** overlapped GCL

h [m]	d overlap [m]						
	0.01	0.02	0.10	0.15	0.20	0.30	0.50
0.3	0.60	0.31	0.08	0.06	0.05	0.04	0.03
0.5	0.99	0.51	0.12	0.08	0.07	0.05	0.04
1	1.96	0.99	0.21	0.15	0.12	0.08	0.06
2	3.91	1.96	0.41	0.28	0.21	0.15	0.10
4	7.80	3.91	0.80	0.54	0.41	0.28	0.17
8	15.57	7.80	1.57	1.06	0.80	0.54	0.33

Permeation "Q" in l/overlaps*/day through an GCL overlap "d" (* approx. 50 rolls in 10,000 m²)

Figure 10 Calculated permeation only through the overlap areas of a project with 10,000m² installed GCL

When water encounters a GCL, it will not flow directly through it. The complexity of the nonwoven geotextile surface and the swelled bentonite core will cause liquid to move laterally in its search for a downward path. Because of this, the overlaps between GCL panels must provide security to prevent a breach. Bentofix® standardly impregnates during manufacturing both longitudinal overlaps with 50cm of high-swelling powdered sodium bentonite to ensure a firm, liquid-deterring area. Bentofix® BFG is even impregnated with an

additional, uniform layer of sodium bentonite powder across its entire nonwoven surface. This advance is ideally suited for pond and waterproofing applications, since the outer layer of the nonwoven geotextile creates an intimate contact zone in overlap areas. In general, the wider the bentonite impregnated overlap section is, the better it performs. Figure 10 reveals a strong contrast between thinner and wider bentonite impregnation at the overlaps. As can be seen, thinner overlaps, such as 1–2cm, present significantly higher rates of permeability - not what one wants in a barrier application. More bentonite in the overlaps means a safer design and a GCL that will continue to meet performance expectations over the long term.

7 Upper GCL Facing the Cover Soil Placement

GCLs are covered almost immediately following installation to protect them against free swelling of the bentonite. But the placement of the cover soil itself can threaten the GCL. Here, the upward-facing layer of the GCL is critical to protection. The GCL cover layer's geotextile type, strength and thickness are key concerns for proper selection. A nonwoven upper geotextile, as used in Bentofix® GCLs, with its minimum mass per unit area of at least 200g/m², protects against installation damage and additionally against bentonite migration. It also provides security against uneven point-load pressure that could be caused by uneven aggregate cover soil.

Higher mass per unit area geotextiles are available for projects that require even more robust protection against cover soil thickness, site use, and available cover soil quality. In cases where interface shear strength is of concern, GCLs with a nonwoven on both sides (one layer of which is always scrim reinforced) are the way to go.

Figure 11 Installation of soil on top of a Bentofix® GCL

For a first assumption, the relationship between the interface friction angles of geotextiles to soils can be assumed by the given equation $\lambda = \tan \delta' / \tan \varphi'$ in Figure 12 and on comparable shear box test results. The internal soil friction ($\tan \varphi'$) and the interface friction ($\tan \delta'$) provide a friction coefficient λ [-] as comparable parameter. The friction coefficient of exemplary shear planes with Bentofix ® GCL is listed. Estimated values for soils placed against the coated Bentofix® side are similar to those of smooth geomembranes. In any case these estimations cannot replace shear box tests with site soils.

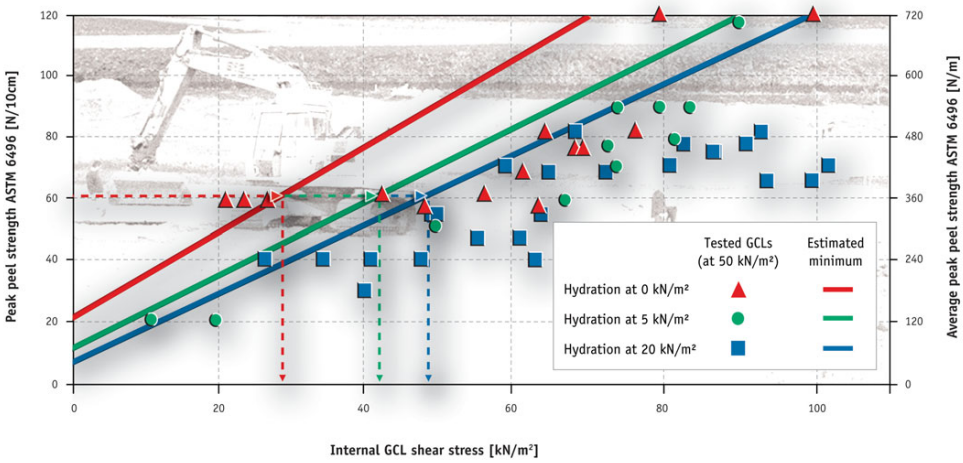
Figure 12 Estimation of interface behaviour of a GCL (reg - regular, without TL TL - Thermal Lock NW - needle-punched nonwoven)

Soil type	Cohesive soils						Fine non-cohesive soils						Fine non-cohesive soils					
Friction coefficient λ [-]	0,6 ~ 0,75		0,75 ~ 0,83		0,75 ~ 0,92		0,65 ~ 0,8		0,8 ~ 0,85		0,88 ~ 0,94		0,75 ~ 0,85		0,8 ~ 0,9		0,9 ~ 0,97	
interface geotextile	Woven (reg)	Woven (reg)	Woven (TL)	Woven (TL)	NW	NW	Woven (reg)	Woven (reg)	Woven (TL)	Woven (TL)	NW	NW	Woven (reg)	Woven (reg)	Woven (TL)	Woven (TL)	NW	NW
Internal soil friction angle [°]																		
22	13,6	16,9	16,9	18,5	16,9	20,4	14,7	17,9	17,9	19,0	19,6	20,8	16,9	19,0	17,9	20,0	20,0	21,4
23	14,3	17,7	17,7	19,4	17,7	21,3	15,4	18,8	18,8	19,8	20,5	21,8	17,7	19,8	18,8	20,9	20,9	22,4
24	15,0	18,5	18,5	20,3	18,5	22,3	16,1	19,6	19,6	20,7	21,4	22,7	18,5	20,7	19,6	21,8	21,8	23,4
25	15,6	19,3	19,3	21,2	19,3	23,2	16,9	20,5	20,5	21,6	22,3	23,7	19,3	21,6	20,5	22,8	22,8	24,3
26	16,3	20,1	20,1	22,0	20,1	24,2	17,6	21,3	21,3	22,5	23,2	24,6	20,1	22,5	21,3	23,7	23,7	25,3
27	17,0	20,9	20,9	22,9	20,9	25,1	18,3	22,2	22,2	23,4	24,2	25,6	20,9	23,4	22,2	24,6	24,6	26,3
28	17,7	21,7	21,7	23,8	21,7	26,1	19,1	23,0	23,0	24,3	25,1	26,6	21,7	24,3	23,0	25,6	25,6	27,3
29	18,4	22,6	22,6	24,7	22,6	27,0	19,8	23,9	23,9	25,2	26,0	27,5	22,6	25,2	23,9	26,5	26,5	28,3
30	19,1	23,4	23,4	25,6	23,4	28,0	20,6	24,8	24,8	26,1	26,9	28,5	23,4	26,1	24,8	27,5	27,5	29,3
31	19,8	24,3	24,3	26,5	24,3	28,9	21,3	25,7	25,7	27,1	27,9	29,5	24,3	27,1	25,7	28,4	28,4	30,2
32	20,6	25,1	25,1	27,4	25,1	29,9	22,1	26,6	26,6	28,0	28,8	30,4	25,1	28,0	26,6	29,4	29,4	31,2
33	21,3	26,0	26,0	28,3	26,0	30,9	22,9	27,5	27,5	28,9	29,7	31,4	26,0	28,9	27,5	30,3	30,3	32,2
34	22,0	26,8	26,8	29,2	26,8	31,8	23,7	28,4	28,4	29,8	30,7	32,4	26,8	29,8	28,4	31,3	31,3	33,2
35	22,8	27,7	27,7	30,2	27,7	32,8	24,5	29,3	29,3	30,8	31,6	33,4	27,7	30,8	29,3	32,2	32,2	34,2
36	23,6	28,6	28,6	31,1	28,6	33,8	25,3	30,2	30,2	31,7	32,6	34,3	28,6	31,7	30,2	33,2	33,2	35,2

8 The Importance of Adding Confining Stress Prior to Prehydration

Dry bentonite, when in contact with water, swells as water hydrates the bentonite, creating, with the increasing water content, a gel-like structure. The amount of swelling is dependent on the confining stress and the strength of the needle-punched fibre-reinforcement, which acts as a counter pressure against the swelling of hydrated bentonite. To maximize the performance of the barrier, it is recommended to add the confining stress over a GCL prior to any hydration. A minimum 0.3m of confining pressure is required (with traffic > 0.5m), but a far greater factor of safety can be achieved with placing the entire cover soil prior to any hydration. A higher confining stress on a GCL also improves the barrier performance of Bentofix® and acts as a long-term protection against desiccation, root penetration or other stresses.

Figure 13
Influence of internal shear stress if pre-hydrated under different confining stresses and sheared under 50 kN/m² confining stress



9 Robust Geotextiles

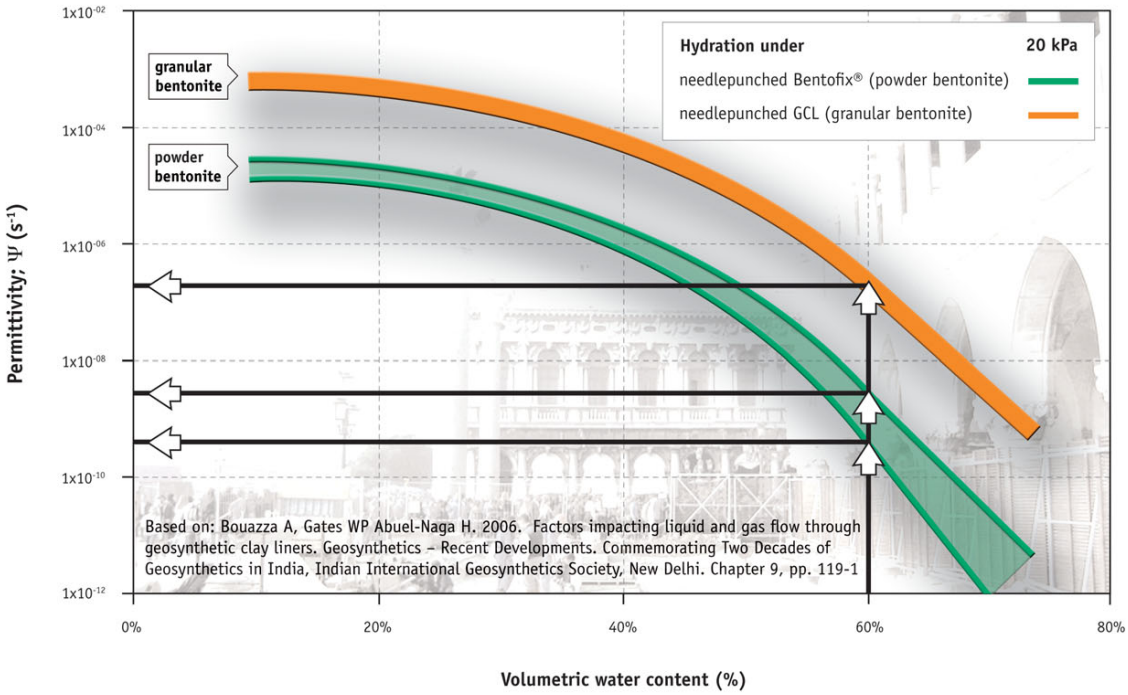
The survivability of all GCLs depends upon its protective geotextiles, which manage the interface shear stresses, protect the GCL from installation damage, and encapsulate the bentonite. The mass per unit area of the geotextile is critical here. The higher the mass, the better the geotextile will perform as a safety measure in the composite GCL system. Nonwoven geotextiles have major advantages compared to slit-film wovens. They typically prevent bentonite from swelling out of the sealing core layer, increase the interface friction value and are more resistant to damage during installation and during the cover soil placement, mainly due to their complex, strong fibre matrix arrangement. It is obvious that the best choice for optimal performance is a nonwoven with a higher mass per unit area. The current minimum standard is 200g/m². This is especially important during installation, during which the top side of a GCL may in fact be exposed to greater stresses than it will be during its designed service life. NAUE Bentofix® is in general installed in such a way that the more robust nonwoven geotextile is faced up towards the cover soil. For critical applications where robustness and interface shear is of heightened importance, NAUE offers Bentofix® GCLs with higher mass per unit area nonwovens than the current industry standard and to ensure resistance against installation stresses the entire GCL should have a tensile strength of minimum 10 kN/m.

Figure 14
Soil placement on top of Bentofix® GCL

10 Powder Outperforms Granules

Manufacturers choose between two grades of bentonite for use in a GCL's core: powdered and granular. NAUE Bentofix® is manufactured only with high-swelling, powdered, sodium bentonite. Powdered bentonite outperforms granular bentonite in key ways. Most notably, powdered bentonite allows a better distribution of the bentonite within the GCL. It does not possess too many voids. Consider that water flows slowly through the voids of soil, so it is important that these voids are small from the beginning. With powdered bentonite the swelling is immediate, because water can immediately surround a larger bentonite surface. With granular, the sealing process is slower; large voids have to close first while water still flows through the GCL. Figure 15 clearly shows that a powdered bentonite achieves a lower permittivity value with the same moisture content than the granular bentonite; under confining stress or without confining stress. Immediate swelling and better distribution of the bentonite leads to a better performing long-term (figure 16) GCL barrier.

Figure 15 Performance of powdered Bentofix® bentonite compared to granular bentonite in correlation to water content and gas permittivity



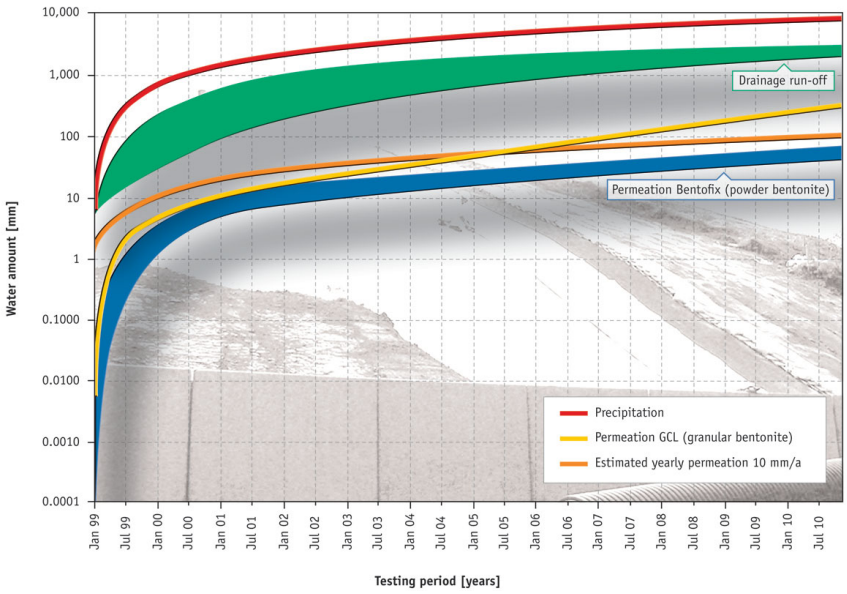


Fig. 16 Precipitation, drainage run-off and permeation values of GCLs under 1m cover soil in German climate.

11 The New Bentogram Design Approach

With its multiple varieties, Bentofix® offers economical, long-term barrier solutions ideal for particular site needs. Each variety is designed to meet specific barrier situations, such as managing hydraulic heads, reducing the risks associated with chemical environments, guarding against root penetration, and accounting for desiccation. The Bentofix® Bentogram (Fig. 17) is a new, easy-to-use tool to help identify the right type of GCL for your installation. To use the Bentogram, identify on a scale of 1 to 10 (10 being the most severe or important) your project's concerns with four key areas that can impact barrier systems: root growth, desiccation, hydraulic head, and chemical influence (see figure 4). The corresponding components chart is then used to help identify the suggested best solution for the selected project. First connect the two opposite sides ("Effect of chemicals" with "Desiccation" and "Root growth" with "Hydraulic head") with a line and the identify the overlapping crossing point. The thicker black-dotted lines refer to the standard differentiation line for the product selection. Additionally, a project's factor of safety can be determined according to Figure 18. These may include

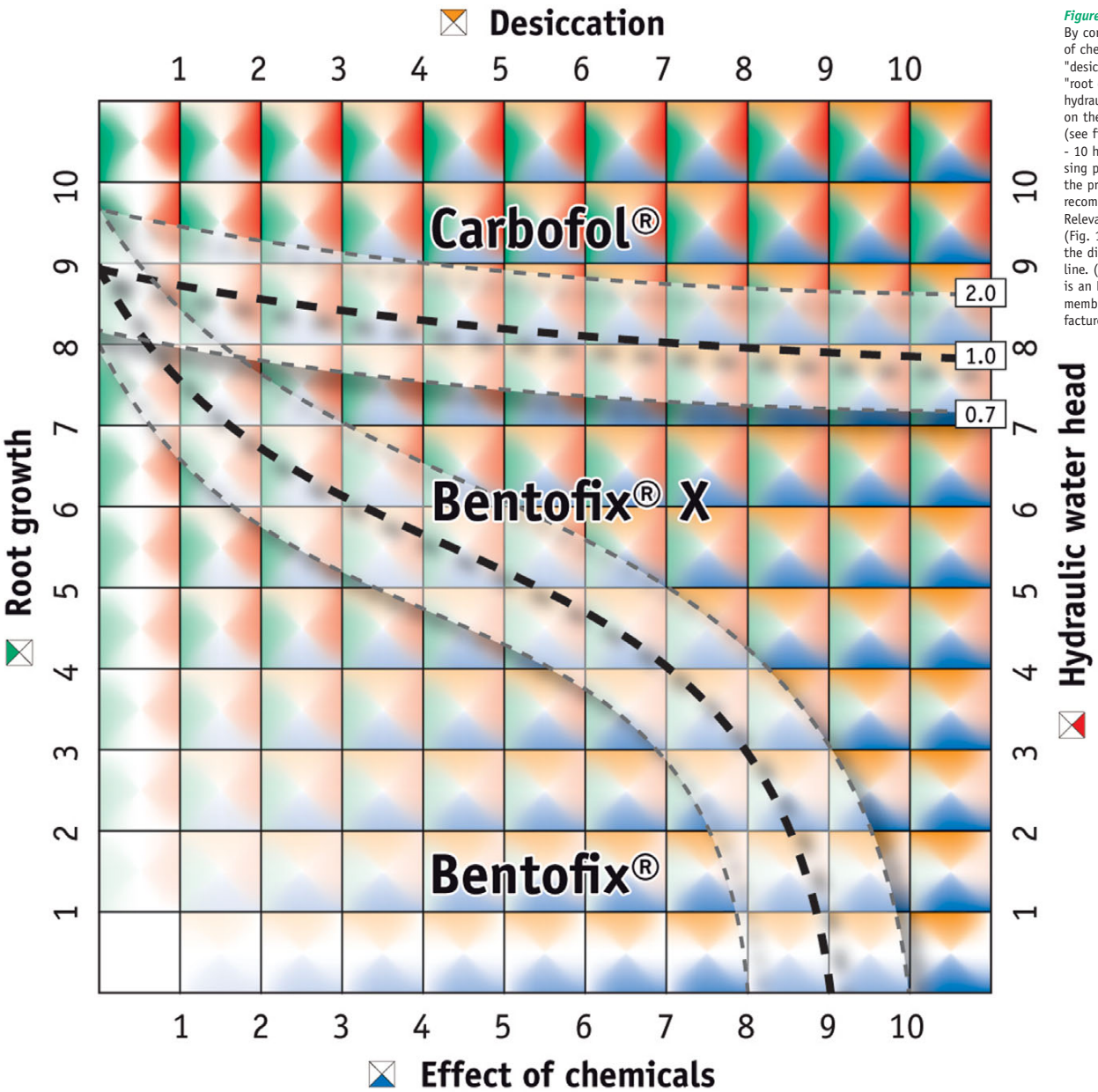


Figure 17
By connecting "effects of chemicals" with "desiccation" and "root growth"with" hydraulic head" based on the importance (see figure 4; 1 lowest - 10 highest) the crossing point indicates the product type recommended to use. Relevant factors (Fig. 18) may shift the differentiation line. (Note: Carbofol® is an HDPE geomembrane manufactured by NAUE.)

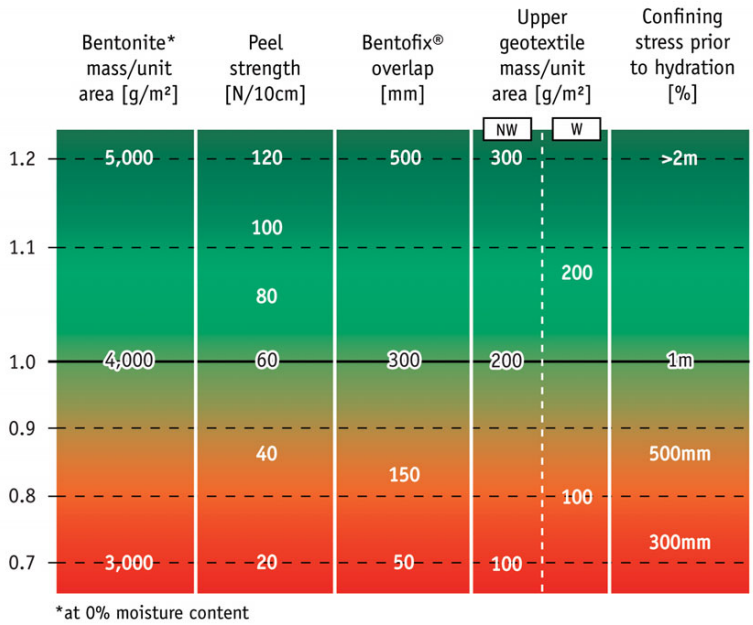


Figure 18
Factor of safety for the determination of the differentiation line for the Bentogram (fig. 17)

NW - nonwoven
W - woven

and consider bentonite mass per unit area, peel strength, overlap, upper geotextile type and mass per unit area, as well as confining stress prior to hydration. (All of these issues are discussed in sections 4 to 10.) By multiplying these factors (> 1.0 with improved or < 1.0 with reduced component properties) the differentiation line for a product selection can shift either way to identify whether the GCL components under project consideration meet the safety expectations and concerns previously marked on the Bentogram. (Note: The dotted differentiation lines are to be used only as a general guide; they are not exact demarcations. Depending on the application, even if your mark is slightly above the line, the product listed beneath may still be a perfectly suitable option.)

Liner system	**Soil permeability** k_L (m/s)	**Transmissivity under GM** θ (m²/s)	**Permeation Q (m³/s/hole)** Hole radius r 1mm	Hole radius r 10mm
Geomembrane (GM) alone	-	-	4.57×10^{-6}	4.57×10^{-4}
GM + 0.6m soil	1×10^{-6}	0 (perfect intimate contact)	3.60×10^{-9}	3.63×10^{-8}
GM + 0.6m clay	1×10^{-9}	0 (perfect intimate contact) 1×10^{-7}	3.60×10^{-12} 2.54×10^{-8}	3.63×10^{-11} 3.56×10^{-8}
GM + GCL (10mm thick)	2×10^{-10} (GCL)	0 (perfect intimate contact) 2×10^{-10}	2.59×10^{-13} 8.46×10^{-11}	4.00×10^{-12} 1.70×10^{-10}

Figure 19
Transmissivity and permeation rates under a geomembrane considering perfect and poor intimate contact between geomembrane (GM) and underlaying soil, resp. GCL, as well as hole size

12 Summary

Engineered barrier systems routinely protect sensitive environmental, industrial and civil installations. Safety is of the utmost importance. While a factor of safety of 1.0 for the selected properties is not a required minimum in GCL barrier designs (See Figure 18's Factor of Safety table) it is a commonly accepted base line, above which barrier performance and design confidence is maximized. The decisions that a designer makes about the GCL itself during material selection heavily influence the ultimate performance and durability of the GCL system. These include decisions (but are not limited to) on the type of bentonite, its mass per unit area, the overlap design, geotextile protection, and confining stress prior to hydration. Bentofix® GCLs are manufactured in accordance with and to exceed international established standards and engineering knowledge for maximum safety and long-term barrier performance. NAUE also offers a wide range of different Bentofix® GCL product types, such as with bentonite impregnated overlap areas, fully bentonite impregnated nonwoven, nonwoven on both sides, GCLs for under-water installation, GCLs with additional attached coating, etc, and NAUE is prepared to support you with knowledge and the right GCL for your project.

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BBA British Board of Agrément Certificate No. 05/4266 — Bentofix® BFG 5000
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