EXCAVATION OF GCL LINING (GBR-C) IN NAVIGATION CANALS AND DIKES AFTER SEVERAL YEARS OF SERVICE

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Abstract: Geosynthetic clay liners (GCL, or clay geosynthetic barriers, GBR-C, according to EN ISO 10318) are well established in landfill design and in groundwater protection, while the use of impermeable linings made of GCL for dikes or levees and navigation canals is much more recent and includes several unique loads. During flood periods the hydraulic head acting on the lining of dikes may be significantly high. However, such loads are applied only during short periods of time, separated by longer periods with no hydraulic loading at all, and the GCL may be stressed by desiccation. In waterways with impermeable linings, desiccation is not to be expected but the linings are exposed to loads such as turbulent flow and hydraulic impact. A further unique point is that the installation of GCLs can be rather difficult if the lining has to be placed under water. Only limited experience has been gained hitherto with this type of installation as the majority of GCLs are installed under dry conditions.

To assess the capability of GCLs to perform as an impervious lining on dikes and waterways, special tests have been developed to be performed prior to installation. Additionally, samples of linings that have been in service for several years have been excavated. Tests on these samples comprised visual inspection and the determination of the tensile strength of the fabric, the bonding strength of base and cover geotextile and the effective hydraulic conductivity of the liner depending on the load history. The test results for excavated samples of a dike and two canal linings are discussed. Based on these results, recommendations are given for future installations.

Keywords: GCL, dam, dike, monitoring, hydraulic conductivity.

INTRODUCTION

The use of geosynthetics as linings in geotechnical and waterways engineering is still relatively new. Geomembranes were first used in a dam in Italy in 1956 (Cazzuffi 1999). Bentonite mats came into use even later so that they are not even mentioned in major codes of practice such as the "Earth Manual" (1998). The current situation regarding the hydraulic applications of both types of lining is documented in Heibaum et al. (2006). The excavation of bentonite mats has provided some information on this type of lining after several years of service and in some cases the findings have already been incorporated into several codes of practice.

BENTONITE MATS USED AS IMPERVIOUS LINERS ON NAVIGATION CANALS AND DIKES

The basic principles for the application of bentonite mats in Germany are laid down in the Recommendations for the Use of Clay Geosynthetic Barriers (EAG-Bentonitmatten 2002). The Recommendations draw a distinction between the uses of GCLs as linings for landfills, hydraulic engineering purposes and for road and railway construction. There are supplementary specifications and recommendations for each type of application with the exception of bentonite mats used in dike construction. The latter is not dealt with separately in EAG-Bentonitmatten (2002) either. For this reason there are frequently great differences in the calls for tenders for bentonite mats for dike construction, depending on which of the above applications they are based on. A working group set up by the German Association for Water, Waste Water and Waste (DWA-Arbeitsthema 2005) published an issue of the "DWA topics" dedicated to linings for dikes in April 2005. The publication includes initial requirements for the materials and installation of GCLs specifically for dike construction but gives no information on the requisite tests. Designers and clients therefore have to draw up specific requirements for the materials and installation of bentonite mats in each individual call for tenders.

There are significant differences between the application of bentonite mats in navigation canals and in dikes. Unlike the linings of navigation canals that are always submerged, the linings in dikes are only subjected to hydraulic loads when water levels are high. Most of the time dikes are “dry”. The installation of bentonite mats in dams and dikes also differs. The linings of navigation canals are generally installed under water while shipping activities continue and covered with a protective layer of riprap. By contrast, dike linings are installed under dry conditions and the protective layer comprises mainly sand or gravel.

REQUIREMENTS AND TESTING

Permeability

The tests to determine the permeability of GCLs are based on DIN 18130 TX DE ST U0. They are conducted on pre-saturated specimens at a cell pressure of 530 kPa and a back pressure of 500 kPa, with a gradient, i, of $\approx$ 500 per centimetre sample thickness (corresponding to the conditions in navigation canals) and with the lowest possible gradient (i $\approx$ 50). The coefficients of permeability, k, are calculated from the measured flow rate, the cross-sectional area of the sample, the selected hydraulic head and the thickness of the sample, which is taken as 1 cm, for a temperature of 10°C. The maximum permeability, k, permitted for bentonite mats used in waterways construction is

$5 \cdot 10^{-11}$ m/s (per 1 cm thickness) and is based on the requirement for cohesive soil linings which are generally installed in layers with a thickness of at least 20 cm. It is not possible to specify a universally valid value for dike construction. The relevant value is selected for each call for tenders, taking account of the specific boundary conditions.

Layers of medium-grained sand had to be placed above and below the bentonite mat samples excavated for examination in order to maintain the in situ geometry of the mats as well as possible during the permeability tests conducted in the laboratory. Specimens tested without sand layers would be pressed flat by the stones in the filter and any differences in the thickness of the bentonite layer would be eliminated. This procedure was also used for new samples obtained from the factory although the samples were first allowed to hydrate completely before being placed in the test apparatus. This is necessary for tests for waterways engineering as the material is meant to be installed under water and is therefore able to hydrate before being subjected to surcharges. The test procedure described is specified for all applications so that the same boundary conditions are ensured during testing when comparative investigations are conducted on new and used material.

The overlaps of GCLs installed under water have to be sufficiently watertight from the outset as subsequent sealing is not possible. Permeability tests must be conducted on an overlap in large cells (Guidelines for Testing Mineral Flexible Linings for Navigable Waterways, RPW 2006). Although GCLs in dikes are installed under dry conditions, it should nevertheless be specified for this application that any need for subsequent sealing of the overlaps must be ruled out as the quality of the overlaps may suffer if the subgrade or bentonite mats on slopes are subjected to traffic.

Robustness (resistance to the loads occurring during installation)

The bentonite mats used in waterways engineering are covered with riprap and the nonwoven or woven materials used must therefore be able to withstand the loads occurring when the rock is placed. The loads are standardised in the dynamic perforation test described in the Guidelines for Testing Geotextiles for Navigable Waterways (RPG 1997). In addition, the mats must satisfy requirements for the minimum tensile strength to ensure that they are robust enough to withstand the stresses occurring during installation.

When the mats are installed under water, the bentonite may hydrate before the riprap layer is placed. It must therefore be ensured that the bentonite is not displaced locally by the impact of the rock. In the test described in RPW (2006) a drop in energy corresponding to the impact energy of a stone of the relevant size class is simulated. The permeability of the bentonite mat in the impact zone of the drop hammer is subsequently checked.

The loads that bentonite mats have to withstand when installed under dry conditions during dike construction are usually lower. This is because greater care can be taken when preparing the subgrade and during installation (although inspection of the procedure is still required) and as heavy machinery is not permitted to operate on the mats until the protective covering has been applied ("DWA topic" 2006). The robustness requirements applicable in road construction (FGSV 2002) could therefore be applied instead of the tests for waterways engineering referred to above. However, the mass per unit area specified by the FGSV cannot be applied to a composite material such as bentonite mats. Not enough experience is as yet available to enable a specific robustness class to be laid down for dike construction so that classes have to be selected on a case-to-case basis. Each of the geotextile components of the bentonite mats must be considered during testing as the upper and lower geotextile layers act together under end-use conditions. However, the bentonite must be removed before the tests as the filling affects the test results.

Durability (resistance under end-use conditions)

Abrasion / surface resistance

Riprap installed on inland waterways is exposed to hydrodynamic actions due to shipping and will therefore move slightly unless it has been grouted in place. The bentonite mats lying beneath the riprap are therefore subjected to abrasive action that is determined in a standardised test described in the Guidelines for Testing Geotextiles for Navigable Waterways (RPG 1997). Abrasive action does not occur in dikes so that the test mentioned here would only be necessary if verification of a particular degree of robustness were required.

Erosion

It must be ensured that geotextiles installed on navigation canals continue to encapsulate the bentonite after exposure to long-term hydrodynamic actions. The reversing turbulent flow test described in RPW (2006) measures the passage of bentonite through the geotextile when the latter is subjected to a pulsating hydraulic load. A maximum value of 5% has been laid down as the upper limit for the loss of bentonite (EAO 2002). No perceptible change in permeability occurs at this degree of loss so the value is a very conservative one. Permeability tests are therefore now performed before and after the reversing turbulent flow test in order to assess the damage caused by erosion.

The hydrodynamic actions occurring in dikes are certainly lower and only occur for short periods of time. However, the reversing turbulent flow test can also be recommended for GCLs subjected to lower levels of exposure to hydrodynamic actions, as stated in RPW (2006), as none of the bentonite mats tested hitherto exhibited a significant reduction in permeability after the test. Investigations such as those described by Rowe and Orsini (2002) are recommended for very high gradients. The authors reported on tests in which water columns of between 17 m and 93 m over a 1 cm thick bentonite mat resulted in a significant increase in permeability, and even in rupture, depending on the product. Again, it is ultimately up to the client to draw up specific requirements.

Freeze-thaw cycles / root penetration

Freeze-thaw cycles may increase the permeability of bentonite mats. Riprap armour layers with the minimum thickness required for navigation canals do not provide adequate protection against frost in zones with fluctuating water levels so that an additional protective layer of gravel or sand is required. The sand or gravel layer also provides better protection against root penetration to which bentonite mats have no resistance. A cover layer with a thickness of at least 80 cm is recommended for bentonite mats used in dikes in the "DWA topic" (2005). Such layers rule out any exposure to frost and also provide adequate protection against root penetration, especially as no vegetation except grass is allowed to grow on dikes.

Dry/wet cycles

Owing to capillary action, bentonite mats used in waterways engineering are always wet, even in those sections that are above water level, so that periodic desiccation does not have to be taken into consideration. However, stress caused by dry/wet cycles does need to be investigated where the GCLs are used as impervious linings for water reservoirs with fluctuating water levels or in dikes. The appropriate requirements have been drawn up for the construction of landfills and generally result in protection being provided by a sufficiently thick cover layer ("DWA topic" 2005).

Ion exchange

Natural or activated sodium bentonite is used in the majority of bentonite mats. In their initial condition, sodium bentonites contain between 50% and 90% sodium ions and between 5% and 25% calcium ions. Even low concentrations of calcium ions in the pore water are sufficient to convert sodium bentonite almost entirely into calcium bentonite in the long term. As a general rule, such conditions are always present on waterways and in dikes. Egloffstein (2000) demonstrated that the ion exchange is accompanied by an increase in the k-value of between a half and one power of ten.

EXCAVATIONS ON NAVIGATION CANALS

Pilot sections with bentonite mats on waterways

Bentonite mats were installed in two pilot sections and monitored very intensively in order to gather experience with their application as impervious linings under the conditions specific to waterways. The first section is located on the Havel-Oder Waterway between kilometre 65.9 and kilometre 66.9 (Fleischer, Schreier 1998). An impervious lining was required as the groundwater level was around 3 m below the level of the water in the canal. Bentonite mats of the type "Bentofix BFG 5000" manufactured by the Naue company were installed and protected with a covering comprising a separate sand mat containing 8000 g/m² sand and a 70 cm thick layer of Class III armourstone (in accordance with the Technical Delivery Conditions for Armourstone (TLW 1997)).

The second pilot section with bentonite mats was installed on the Dortmund-Ems Canal between kilometre 84.3 and kilometre 84.8 in 2000/01. The water level in the canal is a maximum of 2 m above the surrounding land. The bentonite mats used were of the type "BZ 13-B" which are produced by the Naue company and in which the sand mat and bentonite mat are firmly attached to each other. A 60 cm thick protective covering of Class III armourstone was placed on top of the mats. In addition, a 40 cm thick gravel frost protection layer was installed in the zone of fluctuating water levels.

Type tests were conducted to verify that the bentonite mats satisfied the requirements set out in Section 3. The requirements and test methods corresponded to those described in RPW (2006) to the extent that they were already known or specified at the time of installation. The monitoring of the pilot sections included regular observations of the groundwater levels in the ground adjacent to the waterway. In addition, heatable optical waveguides were used to measure the soil temperatures on both banks at regular intervals and were also installed beneath the lining on the second pilot section for the same purpose to enable any minor leaks in the lining to be detected (Fleischer, Schreier 2001). Neither of these indirect investigation methods has hitherto provided any indication of local failure of the sealing function of the bentonite mats.

Excavations on the first pilot section (Havel-Oder Waterway)

Two samples (measuring around 50 cm x 50 cm) were taken from the bentonite mats installed on the Havel-Oder Waterway in 2000 and 2003, around three and five years respectively after installation. One of the samples was taken directly above normal water level and the other at a depth of between 15 cm and 40 cm below normal water level. To do so, the riprap layer had to be removed at those points. The lining was apparently in perfect condition. However, slight local indentations, which had evidently been caused during installation of the riprap layer, could be seen on the surface of the lining (Figure 1).

The sodium ion content of the samples taken from the section above water level in 2000 was found to be between 32% and 47%, while in 2003 it was only between 0.8% and 1.1%, so that the conversion of sodium bentonite into calcium bentonite had been completed in around five years. Virtually complete conversion was found to have taken place by 2000 in the samples taken from the section below water level. The considerably faster ion exchange in this case was probably due to the abundant supply of ions present in the water in the canal.

According to the Supplementary Technical Contract Conditions for Hydraulic Engineering (ZTV-W 2006) the increase in the k-value of samples taken from existing linings must not exceed one power of ten so that allowance is made for the uncertainties in the sampling procedure. In the case of bentonite mats, this means that the k-value of the samples may not exceed $5 \cdot 10^{-10}$ m/s. Out of a total of 18 specimens, 14 were within this limit. The increase in the k-value of these samples by up to one power of ten was probably mainly due to ion exchange. In addition, the influence of frost cannot be ruled out owing to the lack of a protective gravel layer.

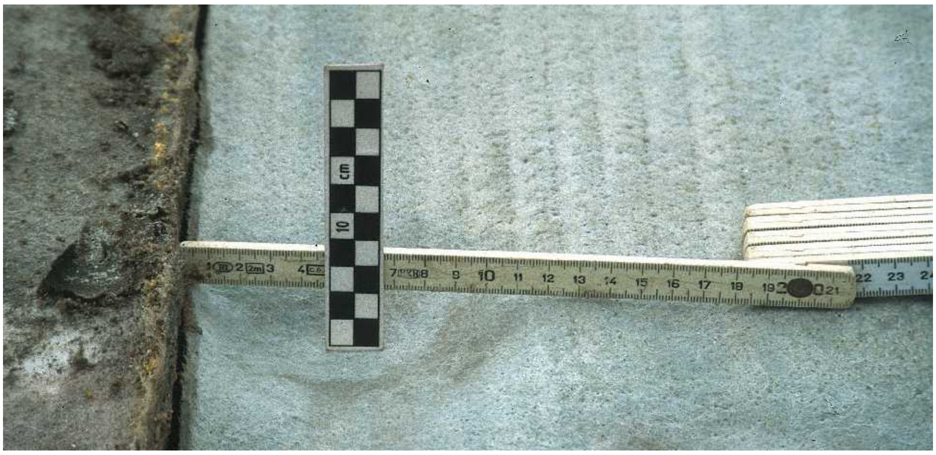

Figure 1. Bentonite mat with indentation caused by riprap

The increase in permeability of more than one power of ten, which was measured in four of the samples was due to local compression of the bentonite caused by the impact of the riprap on the lining (Figures 1 and 2). At the time of construction there was no restriction in the drop height of the stones during installation. Experience has since led to the requirement that the stones to be installed in the zone of fluctuating water levels must be placed on the bentonite mat by an excavator. Furthermore, the gravel frost protection layer which is now required in the zone of fluctuating water levels provides additional protection during installation of the rock armour.

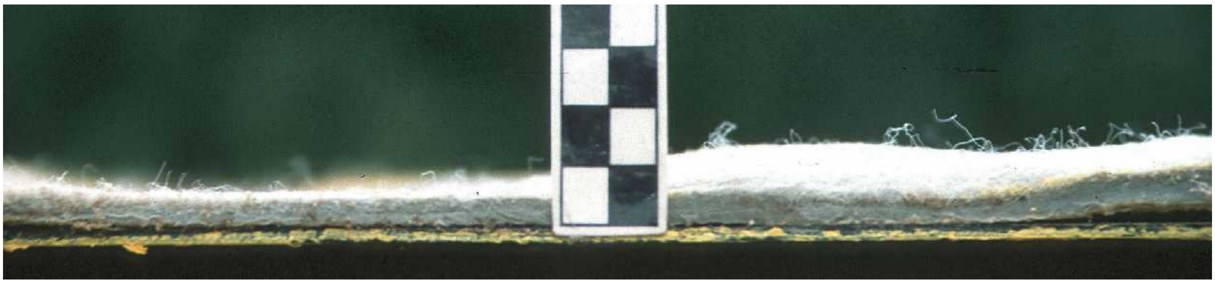

Figure 2. Section through an excavated bentonite mat showing a considerable local reduction in thickness

Excavations on the second pilot section (Dortmund-Ems Canal)

Samples were also taken from the zones above and below water on the Dortmund-Ems Canal in 2004/2005 (around four years after installation). In this case, the bentonite mat is protected by a layer of gravel in accordance with the modified codes. Samples were also taken from the bottom of the canal and the lower part of the slope where the riprap was placed directly on the lining.

The samples taken from beneath the gravel frost protection layer were in very good condition. The thickness of the layer was uniform, at around 1 cm. It could be clearly seen that the bentonite mat had been protected by the gravel layer. By contrast, local indentations caused by the loads due to individual stones were clearly visible in the samples taken from those zones where the riprap had been placed directly on the mat.

The chemical tests showed that the sodium bentonite had been fully converted into calcium bentonite after only four years. The percentage of sodium ions measured in the zones below and above water level ranged from 1% to 6% and the percentage of calcium ions from 72% to 88%.

The results for permeability obtained for the samples beneath the armour layer were similar to those obtained for the first pilot section. In contrast to the results for the samples beneath the gravel layer, the maximum permissible values were exceeded considerably in several cases. This was due to the local compression of the bentonite.

Conclusions drawn from the results

The results of the excavations have shown that, when used on waterways, sodium bentonite will be almost completely converted into calcium bentonite within three to four years. This can lead to an increase in permeability by up to one power of ten. Furthermore, the impact of the riprap and the resultant local flaws in the mats may result in a considerable increase in permeability at those points. Although the local imperfections only lead to a limited increase in the overall permeability of the lining, the system has no reserves as the permeability values are just below the upper permitted limit (ZTV-W 2006), even in the unaffected zones. Such local imperfections are therefore unacceptable. The problem was solved by permitting the use of riprap up to class $LMB_{5/40}$ (without oversized material) as specified in EN 13383-1, i.e. stones with a maximum weight of 40 kg each, on the bentonite mats. Laboratory tests performed in accordance with RPW 2006 have shown that the use of such stones does not result in any unacceptable compression of the bentonite and as a result there were no impermissible increases in the k-value in the impact zone of the drop hammer. Riprap larger than $LMB_{5/40}$ is not permitted to be installed on bentonite mats.

Finally, it must be stressed once more at this point that the method of installation as a whole must ensure that the bentonite mats and the protective coverings are placed correctly under water since visual checks are not possible, in contrast to mats installed under dry conditions. It must therefore be checked that the GCLs satisfy the requirements by conducting type-testing prior to the start of construction work and performing suitability tests and check tests during installation (ZTV-W 2006). For the time bentonite mats may be applied in German navigation canals, if the water level is not more than 2 m above the adjoining terrain.

EXCAVATIONS AT DIKES

Kinzig Dike near Offenburg

Major repairs to the dikes on the Kinzig, a tributary of the Rhine that rises in the Black Forest, became necessary in 2001. The height of the dikes was increased by between 0.6 m and 0.8 m on average, the dikes were strengthened and the waterside slopes were sealed with bentonite mats instead of the conventional clay liners. In order to gain some experience with the installation and long-term performance of GCLs in dikes prior to renewing the lining, a bentonite mat was installed in a defined test area in the foreland of the dikes on the Kinzig near Offenburg in 2001. In this case, the GCL is located in a horizontal position at a depth of 80 cm below a protective covering comprising gravel and sand.

GCLs of the type "B 4000" manufactured by the Naue company were selected. The base geotextile of this type of mat is made of 250 g/m² white polypropylene non-woven material and 100 g/m² white polypropylene slit film woven material, while the cover geotextile is made of 300 g/m² white polypropylene non-woven material. The lower surface of the base geotextile is calendered to fuse the tips of the fibres needle-punched through the fabric. An approx. 30 cm wide strip along the edges of the mats comprises only the base material on the lower surface while the upper surface of the non-woven cover layer is saturated with bentonite in order to achieve an impermeable overlap. The mats have an overall mass per unit area of around 5 kg/m² and a thickness of 8.5 mm at a normal stress of 2 kN/m².

The test area was excavated in July 2007 and samples taken from the mat. It was thus possible to obtain samples after a service period of six years without interfering with the impervious lining system of the dikes. The grass-covered dike foreland is dry when the Kinzig is flowing normally but was flooded several times during the service period.

Figure 3. Section through a sample of a bentonite mat taken from the Kinzig Dike

The excavated bentonite mat was apparently in very good condition. In particular, the section through the mat showed that the bentonite filling was evenly distributed (Figure 3) and did not exhibit any of the depressions known to be caused by riprap even though the underlying soil contained particle sizes over 63 mm in diameter. The suitability test conducted prior to installation showed that the permeability, k, of the new GCL was $1.1 – 1.5 \cdot 10^{-11}$ m/s while the tensile strength was 17.7 kN/m (machine direction) and 30.9 kN/m (cross machine direction).

The coefficients of permeability, k, determined for the excavated samples are shown in Table 1 and range from $2.5 \cdot 10^{-11}$ m/s to $8 \cdot 10^{-11}$ m/s. Compared with the new GCLs, the k-values had only increased slightly, by not more than a factor of 5.

Table 1. Permeability values of the excavated GCLs

Sample	2007-1423	2007-1422	2007-1421	2007-1420	2007-1419
Permeability per 1 cm sample height [m/s] at i ≈ 50	$3.5 \cdot 10^{-11}$	$8 \cdot 10^{-11}$	$3.5 \cdot 10^{-11}$	$4 \cdot 10^{-11}$	$5.5 \cdot 10^{-11}$
Permeability per 1 cm sample height [m/s] at i ≈ 500	$2.5 \cdot 10^{-11}$	$7 \cdot 10^{-11}$	$2.5 \cdot 10^{-11}$	$4 \cdot 10^{-11}$	$3.5 \cdot 10^{-11}$

A tensile strength of 21.2 kN/m was measured in the Naue company's testing laboratory. The results of the chemical tests to determine the sodium and calcium ion contents of the bentonite in the GCL samples show that the sodium bentonite had already been converted almost entirely into calcium bentonite after a service period of six years. The sodium ion content of the bentonite was shown to be as low as 2% to 3% and the calcium ion content as high as 76% to 78%.

Conclusions drawn from the results

The excavated samples and the tests described above show that the bentonite mats will still satisfy the relevant requirements after a period of six years if they are carefully installed and if the protective covering has a depth of at least 80 cm to protect the mats against desiccation, freeze/thaw cycles and mechanical loads as specified in the relevant codes. The tensile strength and permeability values in particular were still maintained after a six-year service period.

SUMMARY

Bentonite mats provide waterway engineers with a further means of sealing navigation canals and dikes. They have clear advantages over other sealing materials as they have a lower overall joint length and greater overlap widths than other types of lining and are factory-made. However, the thickness of approx. 1 cm also means that bentonite mats are much more sensitive to mechanical loading.

Possible changes in the properties after a relatively long period of service can be determined by testing samples excavated from installed bentonite mats. Such tests are a necessary supplement to the indirect methods such as the observation of canals and dikes, monitoring groundwater levels and conducting soil temperature measurements that are usually employed and contribute to gathering information on the application of this relatively new lining method in navigation canals and dikes.

The method of sampling and the investigation of samples taken from bentonite mats used on canals and dikes described in this paper show that the mats evidently continue to satisfy the relevant requirements even after a relatively long service period if they are carefully installed. However, the loads occurring during installation of the mats in navigation canals are much greater than is the case for dikes. This means that there is a greater risk of damage which must be minimised by making sure that the appropriate care is taken during installation and by ensuring that the bentonite mats and the tests meet the relevant requirements. The findings of the excavations have already been taken into account in RPW (2006) that includes modifications to the initial recommendations for geotextiles (see EAO 2002).

A catalogue of requirements dealing specifically with the use of bentonite mats in dike construction has not yet been drawn up. It would therefore be useful to gather more information on this application by carrying out further excavations to enable a basis for such requirements to be established.

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