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Clay geosynthetic barriers performance in landfill covers

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ABSTRACT
Clay geosynthetic barriers (GBR-Cs) used in landfill covers must ensure lining on the long term. The primary mode of ageing of bentonite GBR-Cs in covers is the coupling of cation exchange and hydration-desiccation cycles. The objective of this paper is to synthesize the optimal conditions to prevent a loss of performance of GBR-Cs in covers with time, based on a literature review. Various parameters will be discussed. The literature review will put in light the lack of consistent information from study to study. This enforces the need for a list of information to collect in future excavations. Such a list is proposed in the third section of this paper followed by the presentation of results from recent excavations performed by the first author.

1. INTRODUCTION

The long-term performance of mineral liners in landfill cover systems depends directly on the behaviour of the sealing component in a GBR-C, the bentonite. In a cover system a GBR-C acts mainly in ~~an~~ unsaturated conditions. Therefore the clay tends to dehydrate over time especially in the dry periods of the year with high evapotranspiration and only low precipitation. Furthermore the presence of vital roots on or in the liner will take moisture and enforce the dehydration process additionally.

A cover lining system behaviour is complex and depends on a number of factors among which: (1) the surcharge from the soil cover; (2) the water reservoir of the restoration layer; (3) the drainage layer; (4) roots in the soil; (5) the properties of the adjoining layers; (6) the climatic conditions; and (7) the GBR-C itself. Laboratory tests and computer modelling hardly allow to simulate the long-term behaviour of GBR-Cs. The real performance has to be studied by continuous measurements on site over a reasonable period of time and/or by excavations of GBR-Cs after certain durations (years) in service. Section 2 of this paper is dedicated to a brief presentation of a number of results from field tests and excavations from the literature. The review puts in light especially the lack of consistent sets of data from study to study leading to the difficulty to give conclusions valid in any case for the use of GBR-Cs in covers. Section 3 presents recommendations for sampling of GBR-Cs on site. Finally ~~section~~ Section 4 will be dedicated to the presentation of results obtained on recent excavations.

2. PREVIOUS STUDIES ON GBR-C PERFORMANCE IN COVERS

Tests field studies and excavations were performed in the past to evaluate the performance of GBR-Cs in landfill covers. Excavations can show the state of GBR-C at a given time. Test fields and lysimeters can give information on the behaviour of the system, collecting and registering continuously all water balance data over years, to check the efficiency of GBR-Cs. A number of conclusions were obtained from those studies regarding the influence of roots, cation exchange and desiccation, composition of capping system and thickness, climatic conditions and GBR-C features that will be subsequently discussed.

2.1 Influence of roots

Roots can have two effects on the performance of a GBR-C in a cover. First, roots may have an effect on the dehydration of mineral liners in landfill cover systems (Mansour 2001, Melchior 2002). Roots which reach the mineral liner e.g. a GBR-C will take the moisture directly from the clay whatever the depth of the liner. This may enforce the dehydration process of a GBR-C in addition to thermal gradients in a landfill capping system. Second, roots can have an influence of the permeation of a GBR-C. Indeed if a root penetrates a liner and as long as a vital root is still alive the permeability of the liner might not change or even be improved (Cazzuffi & Crippa 2004). In a later stage if the roots die there will be a leakage by the root itself and the percolation will increase locally.

The choice and care of the vegetation should be considered on the thickness of the restoration layer, respectively the thickness of the restoration layer must be adapted to the intended vegetation. As trees and bushes are very problematic in terms of root depth, which would require restoration layer thicknesses of minimum 3 m, the aim for the vegetation should be green land (meadow). This can be cultivated and therefore reduce the growths of roots by limiting the kind of plants (Ramke 2003), but if the restoration layer is too dry the roots will go deeper to take moisture from the lower sections.

2.2 Cation exchange and desiccation

The causes for desiccation of mineral liners can be the capillary rise of water from the mineral liner in the restoration layer right above and the convective water vapour transport in the drainage layer. The use of GBR-Cs in capping systems is problematic if they are not adequately protected (Melchior 2002, Benson et al. 2007). It has to be expected that when desiccation and ion exchange take place after a short period of time irreversible damages to the GBR-C will occur. Indeed as shown by Sporer and Gartung (2002a) the conversion from Na to Ca bentonites is complete within a few years under the widest range of conditions. According to values from 12 excavations mainly of landfill cappings reported by Egloffstein (2001) the ion exchange usually takes approximately 1 to 2 years when the GBR-C is used in unsaturated conditions. Further, it has been established that due to cation exchange, the permittivity of the GBR-C is about one order of magnitude greater than that of the original Na bentonite as long as there are no desiccation cracks. When desiccation cracks occur the cation exchange in the interlayers prevents the desired self-healing of the fissures. The ensuing leakage cannot be avoided. Even a single desiccation event has an extremely pronounced negative effect on the self-healing capacity of Ca bentonites (Sporer and Gartung 2002b). The observation made by some authors that cracks in bentonite resulting from desiccation do not re-close after re-wetting (Melchior 2002) may not be solely attributed to ion exchange but also to an irreversible change in the structure of the bentonite. Under certain conditions like new sodium GBR-Cs (Sivakumar Babu et al. 2001) or only slightly exchanged sodium GBR-Cs it might be the case that those fissures would close again. This emphasizes the need to prevent desiccation of the bentonite in cap seals.

2.3 Composition of capping system

The “degree of desiccation” depends on many factors such as load from soil cover, water reservoir of restoration layer, drainage layer, roots in the soil and properties of the adjoining layers (Sivakumar Babu et al. 2002). Thus to create a system to cope with the risk of desiccation, all components of the whole capping system including subgrade, drainage layer and topsoil should be taken into account. The material properties, the placement of the soil and the thickness of the topsoil layers should be considered on a site specific basis.

2.3.1 Restoration layer

The thickness of the top soil cover of surface sealing should not be designed just to satisfy the minimum requirements but to take into account the conditions at each individual site (Henken-Mellies and Zanzinger 2004, Henken-Mellies 2005). The soil must be chosen so as to ensure a steady wet climate in the soil pores above the GBR-C.
From various experiences (Arlst & Wolsfeld 2004, Heerten 2004, Heerten & Maubeuge 1997, Heyer 2000, Maile 1997, Maile et al. 1998, Siegmund et al. 2001, Sporer 2002) in Germany, it appears – by extension in central European climatic conditions – that a 1 m thick restoration layer is sufficient in protecting GBR-Cs from desiccation. No observation of desiccation with cracks in GBR-Cs was made under such conditions in Germany so far. In all cases cation exchange had taken place.

Cover soil thicknesses slightly smaller (0.8 to 0.9 m) in Northern America could not guarantee a good behaviour of GBR-Cs in covers (Meer ~~&~~ and Benson 2007, Mackey ~~&~~ and Olsta 2003). This emphasizes the need for a better knowledge of a number of parameters to better understand the behaviour of GBR-Cs in covers for a number of conditions.

Ramke (2003) summarises the German practise, to protect mineral liners in landfill caps from desiccation. He recommends that a restoration layer must have a minimum thickness of 1.5 m. Under dry climatic conditions (average annual precipitation of less than 800 mm/a) a thickness of 1.8 to 2 m of the restoration layer with water storage function seem to be suitable. At locations without any care of vegetation (natural succession) a clear increase of the cover soil thickness is meaningful. The restoration layer should have a “useful field capacity” as high as possible (ideal 200 mm/m). It should be installed without compaction to fulfil this requirement~~,~~ to have a high water storage capacity. In the top section (0.2 to 0.3 ~~º~~m) humus soil should be used. For thicknesses of less than 2 m a “root barrier” (e.g. a dense gravel layer) in the lower section is advisable. In dry locations a geomembrane could be used.

Till now a site specific design of the restoration layer in a landfill capping system is not possible for the long term. The practise is based on experience as the system is very complex and climate is changing.

2.3.2 Drainage layer

The process of leakage through the GBR-C is not a low and constant flow but a sporadic flow occurring mainly during time of high drainage flow where it can be assumed that a hydraulic head builds up temporarily in the drainage layer, which then causes leakage flow. During most of the time the drainage layer effectively keeps the hydraulic head at about zero and consequently no leakage flow occurs (Henken-Mellies ~~&~~ and Zanzinger 2004).

There must be a separation of the mineral liner and the restoration layer to keep the seasonal alternating suctions in the restoration layer away from the mineral liner. With regard to the minimisation of the convective transport of water (capillary rise of water) and the convective water vapour transport the following has to be noted (Ramke 2003): a ventilation in the drainage layer shall be avoided and fine grained gravel shall be used instead of coarse grained. Fine gravel is sufficient to have in any case an interruption of the capillary rise of water.

It is helpful to have a protection layer above the mineral liner to restrain the seasonal effects on the GBR-C. It could be a sand layer or even a thick nonwoven geotextile. It forms no cracks. It has the ability to store a certain amount of trickled water from precipitation and to supply the mineral layer with that water. Such a protection layer also interrupts the capillary flow upwards.

Drainage geocomposites will fulfil the above discussed requirements on drainage layers better than coarse gravel layers. From the authors’ point of view the advisable choice of special layers above the GBR-C for the long term functioning of mineral liners would be to put the following different layers above the mineral liner: sand layer, drainage geocomposite and thick restoration layer.

2.4 Climatic conditions

The weather conditions in an average as in an extreme year should be known and taken into account while planning a cover system. It has been shown that a 0.75 m thick cover in a landfill in North America (continental climate) can be insufficient to protect GBR-Cs (Benson et al. 2007, Mackey ~~&~~ and Olsta ~~2002~~2003, Meer ~~&~~ and Benson 2007). Climatic conditions may have an influence as landfills in Central Europe (oceanic climate of Western Europe) with soil cover thickness of 1 m proved to be sufficient. The findings from Germany could roughly be used for North France but probably not for South France (Mediterranean climate). But climate is difficult to predict and actually climate is changing everywhere very fast. Some places will become drier whereas others will receive more rain than in the past. It is advisable to plan a landfill cover system for a dry climate even if the site is not categorized as dry location so far. As a compensation for critical climatic conditions the use of a mighty restoration layer and other layers described in ~~section~~ Section 2.3 is strongly recommended.

2.5 GBR-C features

Some manufacturers use granulated bentonite and others use powdered bentonite. The bentonite is either a natural sodium bentonite or an activated calcium bentonite. The clay could come from very different resources around the world and it is treated in a certain way as the bentonite must provide its best performance depending on the application, e.g. landfill cover lining. Most use sodium bentonite but some use also pure calcium bentonite. As calcium bentonite has not the same sealing properties than sodium bentonite, the mass per unit area is nearly double compared with a GBR-C with sodium bentonite. Some GBR-Cs have a foil inside to reduce desiccation of the bentonite and to improve the resistance against root penetration for certain plants or they have two light GBR-Cs needle punched together to a heavy ~~one~~ one with the aim that the upper GBR-C protects the lower GBR-C against desiccation as a nonwoven interlayer might act as a capillary breaking layer.~~.~~

Comment [n1]: What is the impact of the content of thids sentence for the paper. I am not sure it is appropriate unless we give a recommendation for a reason or another to use those products in such or such a situation. Views?

As poor and bad performance was found for GBR-Cs with very low mass per unit area (<4 kg/m²) (Benson et al. 2007, Melchior 2002) sometimes combined with low soil cover thickness (<0.5 m) the minimum dry mass of bentonite per unit area is seen as the basic differentiation feature for GBR-Cs. As a recommendation from the authors point of view the minimum dry mass of bentonite per unit area should be 4.5 kg/m² for sodium bentonite respectively 9 kg/m² for calcium bentonite in a GBR-C.

3. RECOMMENDATIONS FOR FUTURE EXCAVATIONS OF GBR-C

The relevant information is not always given in the literature. Data are difficult to compare from excavation to excavation. Therefore it is recommended to follow the following methodology while extracting GBR-C samples. The list of recommendations given below corresponds to an ideal situation. Economic reasons can lead to necessary reductions in the number of tests that can be performed.

3.1 Product description

The clay geosynthetic barrier needs to be described with details: (1) description of the synthetic components; (2) bonding process of the GBR-C like needle punching, stitch bonding or adhesive bonding; (3) type of bentonite like sodium bentonite, natural or activated sodium bentonite or calcium bentonite; (4) origin of bentonite, powdered or granulated bentonite. When was the GBR-C installed? Was the GBR-C installed in "dry" condition or in a pre-swollen condition? What were the initial properties of the GBR-C at the time of installation? Give the mass per unit area of the bentonite at a given moisture content. Give the properties of the bentonite like swell index, water absorption and fluid loss. Ask for data which the manufacturer could provide ~~you~~. Ask for quality control data from the factory production control and or from the construction quality assurance if available.

3.2 Site description

Categorize the location in "climate regions" (Mediterranean climate, oceanic climate and continental climate). Give the altitude. Is it a coastal area or a mountainous area? Collect the available climatic data (average annual precipitation, average monthly precipitation and average monthly temperature). What was the local precipitation in litre per square metre per year? Is it a sunny or a shadily place like in a forest or in a valley? Is it a windy place? What is the potential evapotranspiration in mm annually on average? Describe the vegetation (plant cover). Check the plants and their size depending on the assumed root system and root length? Have the samples been extracted at a slope or on a plateau? Is the orientation of the slope in south direction or north direction? In which season has the excavation been made – winter or summer?

3.3 Soil description

The dig can be opened with an excavator. The last 0.2 m has to be dug out by hand with a shovel. The size of the open laid GBR-C should be 1 m x 1 m as a minimum. Describe nature and kind of each individual layer of the cover soil and measure the thickness of each layer. Take undisturbed samples from each layer. Measure the soil density and give the soil compression ratio. Determine the hydraulic conductivity to water. Determine the field capacity of the soil. Take disturbed samples from the soil. Determine the particle size distribution of the soil. Determine the humus content (TOC). Measure the content of cations in the soil and especially calcium. Check the iron content of the soil. Describe the roots in the soil and the maximum depth of those roots. Describe also the soil beyond the GBR-C and determine the cation content of that soil. Describe other geosynthetics – if there are – and take samples. Do drainage geocomposites show eventually ferric incrustations?

3.4 GBR-C sampling

The GBR-C has to be dug out very carefully. It is not allowed to set a foot on the GBR-C. At least two samples about 0.3 m x 0.3 m shall be cut by using a sharp carpet knife. Take pictures from each part of the excavation. Mark the samples with a unique number and an arrow in the machine direction on the top side of each sample. Are there roots in contact with the GBR-C samples or do the roots even penetrate the GBR-C samples? Are these roots vital or dead? After cutting the samples take them out carefully. Avoid any bending on the samples. What do the cutting edges of the samples look like? Are there any cracks in the bentonite? Are there any changes in colour in the bentonite? Describe any distinctive features. Put each sample into a separate plastic foil to avoid any evapotranspiration. Store them immediately in a rigid box, so that the samples are protected against any damage. The GBR-C samples have to be kept undisturbed. Make sure, that during handling and transportation any loads or high temperatures are avoided on the samples. Keep them in a cool and dry place to avoid any dehydration. Cover and close the hole after the excavation with a new piece of GBR-C in the appropriate way. The standard EN ISO 13437 is helpful in planning any sample extraction in the field.

3.5 Laboratory tests on GBR-C

Cut specimens from the first sample for the following tests:

- water permeability of GBR-C (e.g. NF P 84-705 or ASTM D 5887);
- mass per unit area of GBR-C (EN 14196);
- mass per unit area of bentonite (EN 14196);
- moisture content of bentonite (ISO 11465);
- swell index of bentonite (e.g. XP P 84-703 or ASTM D 5890);
- water absorption of bentonite (e.g. XP P 84-704 or DIN 18132);
- fluid loss of bentonite (ASTM D 5891);
- cation exchange capacity of bentonite (e.g. NF X 31.130); ~~and~~and
- mole fraction of cations (sodium, calcium, potassium, magnesium) of bentonite (e.g. NF X 31.130).

~~The permittivity can be determined in flexible wall permeameters following ASTM D 5887 or in rigid wall permeameters following NF P 84-705.~~The standards given above are an indication and they are not restrictive.

The permittivity can be determined in flexible wall permeameters following ASTM D 5887 or in rigid wall permeameters following NF P 84-705. The hydraulic gradient could be applied to a water head of 0.3 m. The confining pressure should be equal to the real surcharge at the site. As permeant liquid typically deionised water is used but in certain cases also rainwater percolation or a NaCl or $CaCl_2$- solution with a certain concentration can be used. The cutting of specimens from the hydrated GBR-C sample has to be prepared with great care to avoid any changes by the handling and later on with the installation of the specimens. Individual treatments and experience is necessary for the hydraulic tests of hydrated GBR-Cs.

The minimum test on samples from the field are: permittivity, moisture content, mass per unit area, swell index, cations determination. For any control test it is very useful to have data on the same properties from the time of installation of the GBR-Cs, and especially on bentonite features. The second sample should be checked for cracks with X-ray images.

Comment [nt2]: Maybe for the international context there could be other standards or different standards to mention?

4. RESULTS OF RECENT EXCAVATIONS

The described excavations follow the standard procedure including the basic tests.

The first author investigated the behaviour of three different GBR-Cs used in three landfill closures; two in northern Bavaria, Germany (landfill A and B) and one in Westphalia, Germany (landfill C). In landfill A (Fig. 3 and 4) the mass per unit area of the sodium bentonite GBR-C was 10.5 kg/m² at a 89% water content, the swell index was 14 ml/2g and the water absorption 255%. The permittivity ranged from 1.8×10^{-9} s^{-1} to 2.7×10^{-9} s^{-1} at 15 kPa confining pressure. The soil thickness on top of the GBR-C was ~~65 c~~0.65 m including 0.1 m sandy gravel above the GBR-C (Fig. 1). This shows that sodium bentonite has partly changed to calcium bentonite, but the permeability is still representative for a sodium bentonite GBR-C. So far the GBR-C shows an excellent performance even after 5 years in service and under a shallow cover soil of only 0.65 m. Roots have not been found on the GBR-C

Figure 1.~~:~~ ~~C~~cover soil in landfill A

Figure 2.~~:~~ ~~C~~cover soil in landfill B

In landfill B (Fig. 5 and 6) the mass per unit area of the calcium bentonite GBR-C was in the range of 16.3 to 19 kg/m² at 70 to 80% water content, the swell index was 7 ml/2g and the water absorption 190 to 300 %. The permittivities ranged from 5×10^{-9} s^{-1} to 8×10^{-9} s^{-1} at a 30 kPa confining pressure. Samples were taken on top of the landfill 6.5 years after construction. The soil thickness on top of the samples was close to 1.2 m (Fig. 2). The used calcium bentonite remained unchanged 6.5 years after installation. The barrier function is fulfilled. Roots have reached the liner even in 1.2 m depth plus a drainage geocomposite, but no penetrations of the GBR-C were found.

In the third landfill C (Fig. 7 and 8) a sodium bentonite GBR-C was used. After 11 years samples have been taken. The mass per unit area was about 10.3 kg/m² at a water content of 85%. The swell index was 7 to 8 ml/2g and the water absorption was 164 to 190%. The measured permittivities ranged from 1.~~9~~6×10^{-8} s^{-1} to ~~values lower than~~ 1.9×$10^{-8}$$s^{-1}$ at 20 kPa confining pressure. ~~Surprisingly~~ ~~T~~The ~~lower~~ permittivities ~~were~~ found were the same for the specimens without and with root~~were~~ penetration~~ed with roots~~. The cover soil thickness was 1 m plus a drainage geocomposite. The data found were typical for a GBR-C after cation exchange. But the GBR-C still fulfils its function as a barrier in a landfill cover system.

Figure 3. Excavation on landfill A

Figure 4. Cut GBR-C and subgrade in landfill A

Figure 5. Excavation on landfill B

Figure 6. Cut GBR-C and subgrade in landfill B

Figure 7. Excavation on landfill C

Figure 8. GBR-C with roots and subgrade in landfill C

5. CONCLUSIONS

As a recommendation from the authors point of view the minimum dry mass of bentonite per unit area should be 4.5 kg/m² in a GBR-C containing sodium bentonite (respectively 9 kg/m² calcium bentonite) and the minimum height of the cover soil (restoration layer) should be 1.5 m in Western European oceanic climate. The vegetation should be cultivated to reduce the growths of roots. The restoration layer should be installed without compaction to provide a high water storage capacity. For thicknesses of less than 2 m a “root barrier” in the lower section is advisable.

Drainage geocomposites should be used as drainage layers instead of coarse gravel layers.

A protection layer (e.g. sand) above the mineral liner has the ability to store a certain amount of trickled water from precipitation and to provide that water for the GBR-~~C.~~C.

Comment [n3]: give again the ideal constitution of the cover?

The ideal constitution of the landfill cover would be to have a sand layer above the GBR-C. Above the sand layer a drainage geocomposite shall be installed followed by a thick restoration layer.

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