*Geosynthetics - 7th ICG - Delmas, Gourc & Girard (eds) © 2002 Swets & Zeitlinger, Lisse ISBN 90 5809 523 1*

# Design of landfill cover lining systems with geosynthetic clay liners (GCLs)

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ABSTRACT: Geosynthetic clay liners (GCLs) are currently used in different types of landfill cover systems. Generally a complete system includes a cover soil layer of approximately 1 m thickness, a drainage layer such as a geosynthetic drainage system (GDS) and a shear strength transmitting geosynthetic clay liner. In the last years a lot of different research projects have taken place to describe the efficiency of different lining systems based on the use of GCLs. Therefore several test sites have been built and investigated over some years. Test results show a different efficiency varying with the design of the whole system. All research projects published point out that the efficiency of every mineral lining system – especially GCLs with encapsulated high active clay minerals – depends on the water balance between the sealing element and the surrounding soil layers. In this paper the application of the hydrologic evaluation of landfill performance (HELP) model is described under seasonal varying weather and water balance conditions. A special update enables designers to give a more realistic estimation if the influence of drying processes and rehydrating on a GCL permeability is known.

## 1 INTRODUCTION

Geosynthetic clay liners (GCL) are widely used in the geotechnics and hydraulic engineering sector for sealing applications. In 1997, the worldwide sales of GCLs was estimated to be approximately 16 million m², todays figures are considerably higher. As a result of the shear strength required in sloping areas, product types with long-term shearing force transfer (i.e. needle-punched and stitch-bonded GCLs) have found international favour.

GCL's are mostly made of nonwoven geosynthetics and bentonite whereby the nonwoven geosynthetics provide long-term load transmission and internal cohesion and also support the formation of an areal swell counter pressure. With bentonite, on the other hand, it is the mineral component which ensure a permanent sealing effect. This paper takes a look at the factors influencing the sealing effect of a bentonite liner based on the water balance of a capping system and presents a method of evaluating system efficiency. Further major design parameters are interior and exterior shear strength which are to be investigated separately.

## 2 BENTONITE – AN ACTIVE SEALING MATERIAL

### 2.1 *General*

The sealing material in geosynthetic clay liners (GCLs), bentonite, is a naturally occurring mineral clay with very high swelling capacity, high ion exchange capacity and very low hydraulic conductivity. High-quality bentonites, those used in GCLs, mainly consist of the three-layered (2:1) clay mineral montmorillonite (approx. 75 – 90 % of their weight).

The clay mineral montmorillonite is one of the best known natural ion exchangers. In most cases, the naturally occurring bentonites are calcium bentonites, natural sodium bentonites are comparably rare. In order to utilize the better swelling properties of sodium bentonite, calcium bentonite for instance is activated with soda (sodium carbonate) and thus the primary calcium ions are replaced by sodium ions (so-called active bentonite) (Madsen/Nüesch, 1994). On the other hand, calcium concentrations in leachates of soil are likely to convert the sodium of the bentonite into calcium. Since calcium is usually the most frequent cation in leachates of soils, the ion exchange of sodium against calcium normally occurs when sodium GCLs are used in such a geochemical environment.

Evaluation of laboratory tests and numerous excavation results have shown that this ion exchange takes one to two years when GCLs are used in partly saturated areas (e.g. landfill cappings). This exchange occurs until an adsorption balance between the ion distribution at the bentonite and the ionic concentration in the soil solution is achieved. When the ion distribution of the bentonite has adapted to the geochemical environment according to the natural exchange balances, it will practically remain unchanged.

Calcium bentonites have, by nature, a more coarsely aggregated internal structure providing a higher permeability rate than in sodium bentonites. Furthermore, they have considerably fewer swelling properties and thus are less suitable for providing a tight seal in cases of perforation. In contrast, sodium bentonite liners provide higher product-immanent safety due to installation damages on site (Egloffstein, 2000).

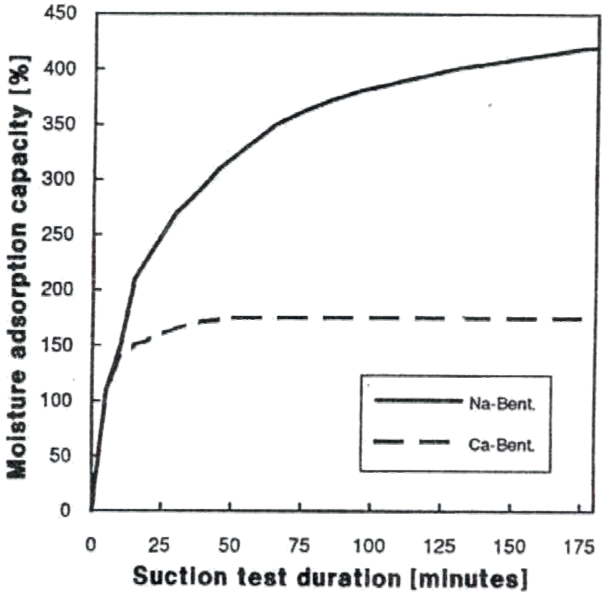

Figure 1. Differences in swelling capacity of sodium and calcium bentonite

### 2.2 *Shrinkage and swelling*

Shrinkage and swelling are physical processes in soils and the reaction of a mineral structure on moisture present. In geotechnics, the plasticity factor $I_p$ is used to evaluate the sensitivity with which a cohesive soil reacts to the addition or removal of moisture, whereby a cohesive soil will have a higher degree of moisture-sensitivity the smaller the $I_p$ factor is ($I_p = w_L - w_P$). Table 1 shows an overview of typical soil characteristics of bentonites in comparison with natural clay.

| Type of soil | Liquid limit $w_L$ (%) | Plastic limit $w_P$ (%) | Plasticity factor $I_P$ (%) | Activity factor $I_A$ (-) |
|---|---|---|---|---|
| natural clay | 20 - 60 | 10 - 20 | 10 - 40 | 0,4 – 0,9 |
| natural Ca-bentonite | 100 – 150 | 30 – 50 | 70 – 100 | > 1 |
| natural Na-bentonite | 500 – 700 | 50 - 70 | 450 - 630 | >> 1 |

Table 1: Typical Soil Characteristic Values

The swelling behaviour of the clay is closely connected to the water adsorption capacity of the clay minerals. An existing swelling potential can, for example, close cracks in the form of the so-called "structure-healing effect". The better the swelling behaviour, the greater the structure-healing effect.

As the consistency of a cohesive soil – including bentonites – significantly determine the physical properties of the soil, knowledge of its liquid and plastic limits for evaluating swelling and shrink behaviour as well as its structure-healing properties when rehydrated are of fundamental importance. The first cracks resulting from dehydration in a thin, cohesive surface soil already occur at a water content above the plastic limit (Krabbe, 1958) namely at the transition from a single axial (purely vertical) to a triple axial (vertical and horizontal) shrinkage. Krabbe observed the first cracks in a 1.5 cm thick surface soil sample of various natural clays without load at a temperature of 20° C when the soils reached a moisture content corresponding to 1.25 to 1.5 times the water content at plastic limit.

Applied to bentonite liners, it can be derived from the fundamental physical soil values made for calcium bentonite and sodium in Table 1 that both types of bentonite are susceptible to cracking when the natural water content drops below 80 – 90 % and there is no load. Subsoils have the impact of a mechanical load and thus increase the particle-to-particle friction of the bentonite matrix. This increases the internal strength and reduces the formation of cracks.

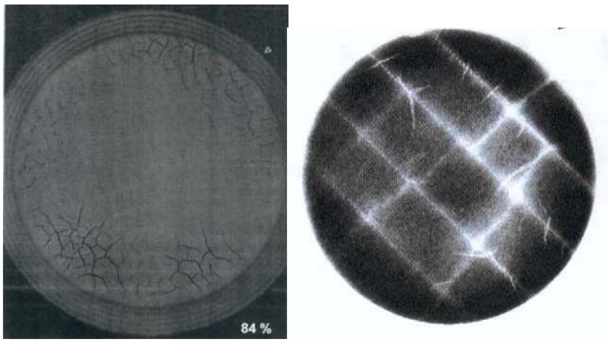

Figure 2. x-ray pictures of a non-woven needle-punched Na-GCL after ion exchange (w = 84 %, left, more fine fissures) and a woven stitch-bonded Ca-GCL (w = 82 %, right, less greater fissures), see Siegmund et. al. 2001

Generally, it can be determined that in laboratory trials carried out under comparable conditions, these water balance values according to Krabbe can be confirmed in principle. Furthermore, it is apparent that the production form – needle-punched /stitch-bonded – has a distinct influence on the structure of the cracking. The needle-bonded product (Fig. 2, left) shows a relatively even distribution of more fine cracks whilst the stitch-bonded product has fewer (Fig. 2, right), but larger cracks which, as the x-ray illustrates, lead to a “ladder-type“ crack structure with the sewing thread.

A series of further tests confirmed the excellent structure-healing properties of needle-punched GCLs after drying out if there was enough load.

- mineral swelling capacity,
- the degree of dehydration,
- the quantity of water available when rehydrated and
- the existing load.

In the case of extreme desiccation leading to a water content of between 50 and 70%, ion-exchanged sodium bentonite or natural calcium bentonite is present in a stiff or semi-solid state. Due to reduced moisture adsorption capacity those bentonite softens only slowly. At this stage of rehydration, bentonite liners require only small quantities of water – less than approximate 2 1/m², which corresponds with typical top drainage rates depending on the type and thickness of the cover soil and climatic conditions. This explains why dehydrated bentonite liners allow short-term increased leaching rates during the rehydration and structure-healing process. Egloffstein documented in comprehensive tests that the structure-healing process in needle-punched bentonite liners after dehydration and ion exchange from different landfills can very well take place in a few weeks. During this time of rehydration a higher rate of drainage water than necessary for structure healing could percolate through the GCL liner with a decreasing tendency. With a load corresponding to approximately 1 m cover soil a low, constant permeability level and corresponding sealing effect is reached.

### 2.3 *Conclusion*

As the prescribed physical soil activity factor documents, bentonites are highly-active special clay minerals with – compared to natural clays – strong swelling and shrinking properties. The excellent swelling qualities of sodium bentonites are a major safety contribution against installation damage of sodium GCLs.

After ion exchange, the plasticity value and liquid limit for former sodium bentonite and natural calcium bentonite do not differ significantly. Should the water content fall short, desiccation cracks can be expected. It would appear here, according to current knowledge, that the product form (needle-punched or stitch-bonded) are of importance for the cracking. Analogous to the theory of watertight concrete it should be expected that the structure of a desiccated needle-punched GCL heal faster than stitch-bonded.

The results of comprehensive field tests and laboratory tests have produced favourable assessment of the structure-healing of needle-punched GCLs. It was determined at just 1 m load that the structure-healing process takes 10 to 20 days until a stable permeability value is reached. Only a small quantity of water is required for the structure-healing process.

With this knowledge in mind, the engineer is faced with the task of finding a system construction for capping with bentonite liners which will provide optimum sealing effect for the site conditions present in case of dehydration. The authors have developed a further strategy based on the HELP model (Hydraulic Evaluation Landfill Performance, US EPA, 1994) which also allows variable permeability values to be modelled during the structure-healing process of needle-punched GCLs and to be considered in system comparisons as can be seen as follows.

## 3 MODELLING OF SOIL MOISTURE REGIME IN SURFACE SEALING SYSTEMS

Figure 3 shows a capping system consisting of a GCL as sealing element and a drainage mat as a draining element. The water balance components of the capping system are also shown in Figure 3 and comprise the following: precipitation, evapotranspiration, surface run-off, drainage layer run-off in the drainage layer , leaching through the sealing layer and changes in soil moisture in the recultivation layer. The water balance of surface sealing systems can be calculated by using the HELP model. The above-mentioned water balance components modelled with HELP are calculated dependent on existing climatological, soil-scientific and vegetation-specific parameters measured daily. Whereas the standard version of the HELP model for sealing layers takes a general constant $k_f$ value, the following shows a further development and application of the HELP model taking variable $k_f$ values for single-layer Bentofix® geosynthetic clay liners.

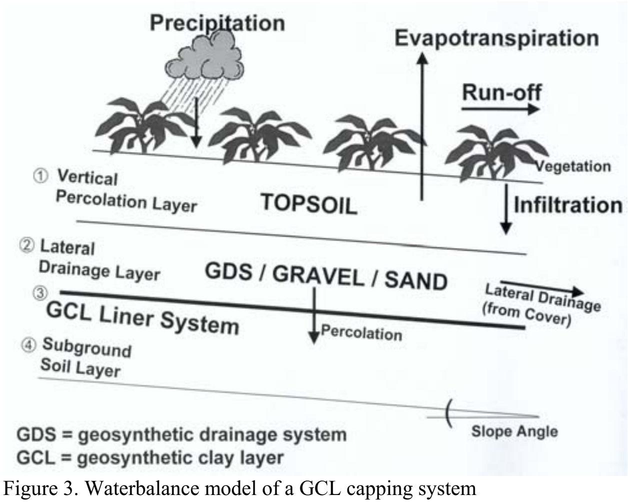

Figure 3. Waterbalance model of a GCL capping system

The basis of calculating the continuous rehydration of a dehydrated needle-punched GCL is described by Egloffstein (2000).

The following is a summarized description of a further technical programme development and the inclusion of a rehydration function with variable k-values to characterize a structure-healing effect after dehydration in the HELP model.

The average moisture retention level over the clay sealing liners (i.e. water resources) calculated using the model are selected as control quantities to determine dehydration and rehydration. During simulation on a daily basis with the HELP model, the question arises as to whether the moisture retention level during the day is zero, meaning there are currently no water resources present. If this phase exceeds the defined time periods $t_{dry}$ without drainage, a sudden increase in permeability to $k = k_{dry}$ is assumed in the programme and water balance calculations are carried out at increased permeability. Egloffsteins investigations document here increased k-values of $k = 10^{-8} – 10^{-7}$ m/s depending on the level of dehydration. However it is known from field and laboratory measurements that in reality the desiccation time lasts several weeks, the model bases on a sudden increase of permeability from one day to the other.

After the dehydration phase the model takes various levels of permeability (daily variations in the $k_f$ values) into consideration during the phase of rehydration whereby these phases are characterized by water resources in the drainage layer i.e. retention level > zero.

The calculation of rehydration and allocation of permeability levels of needle-punched geosynthetic clay liners within the rehydration period are made in such a way that every day a different reduced permeability can be allocated during the daily cycle. The basis of these structure-healing functions are the Egloffstein (2000) investigations. They show that the initial increased permeability for needle-punched GCLs with 4000 to 5000 g/$m^2$ sodium bentonite after ion exchange drops within 10 – 20 days to $k_{cal} = 5 - 8 \times 10^{-10}$ m/s under at least 1m load with even lower permeabilities over the time.

Here various limiting periods are re-considered in order to test whether the rehydration phase continues. Any excess of the defined limiting periods $t_{dry}$ is shown in the model by an immediate jump to increased initial permeability and waiting for rehydration (structure-healing).

## 4 MODELLING OF A GCL-LINER SYSTEM

The following results of site-relevant water balance are based on the described water balance model.

A test plot on the blast furnace flue tip from the Profil Arbed steel company in Esch-Belval, west of Esch-zur-Alzette on the French border of Luxembourg is 45 $m^2$. The thickness of the re-cultivated layer is 75 cm and the thickness of the mineral drainage layer 25 cm. The re-cultivated layer is overgrown with grass. The set-up corresponds to the outline conditions defined by Egloffstein regarding structure-healing. The Schnatmeyer thesis (1998) documents the test field together with measured soil-specific and vegetation-specific parameters. The water balance calculations were carried out using these parameters.

Data necessary for simulating the water balance were not available on a daily basis at the Esch-Belval site in Luxembourg therefore resort was made to corresponding climatic data of a comparable location in Germany. The official measuring station of DWD (German Official Wheather Service) in Hüttersdorf provided data for precipitation, Berus measuring station supplied temperatures and global radiation values came from the measuring station in Saarbrücken. Hüttersdorf and Berus are approximately 60 km south-east of Esch-Belval. Table 2 shows the calculated and measured values of individual water balance components as annual cumulative values.

Table 2: Results of measured and calculated GCL-Liner System-Efficiency

| | | 1 – 12 / first year (sodium dominated bentonite) | | 1 – 12 / second year (sodium ⇒ calcium exchange) | | 1 – 9 / third year[1)] (calcium dominated bentonite) | |
|---|---|---|---|---|---|---|---|
| | | meas. | calc. | meas. | calc. | meas. | calc. |
| ① | Rainfall [mm] | 713 | 736 | 1037 | 980 | 493 | 652 |
| ② | Run-off [mm] | no data | 6 | 8.0 | 7.0 | 3.0 | 7.0 |
| ③ | Drainage [mm] | 245 | 212 | 401 | 312.0 | 45 | 205 |
| ④ | Percolation [mm] | 1.5 | 0.3 | 6.4 | 8.0 | 3.8[2)] | 7.0 |
| | System Efficency ④ : ① [%] | 99.8 | 99.9 | 99.4 | 99.2 | 99.2 | 98.9 |

1) = project terminated in 10/98
2) = no data registered from 14.04. – 26.05.98

Generally a good comparison can be observed between measured and calculated values from the yearly cumulative values which apply to surface run-off and particularly to leaching through the bentonite liner. The differences between the calculated and the measured values of the drainage flow can be mainly contributed to differing precipitation data between the test field and the weather stations used (see above).

In view of the minimization of percolation into the landfill body in the year 1997, 6.4 mm was measured and 8 was calculated - a comparison which can be considered as very good.

On the first view the data of the year 1998 (January to September) show a greater difference in percolation.

The reason for this difference can be found in the outage of measured data for leaching through the bentonite liner on site from 14.4.1998 – 26.5.1998. Regarding to the weather conditions in the second half of March it was assumed for the modelling that the bentonite liner was dried out at the beginning of April. In the first week of April, there was a total of 85 mm precipitation on site and for this period a time-limited, increased percolation of 3.5 mm through the single-layer bentonite GCL until rehydration was calculated. However, it cannot be excluded that this short-term increase in permeability as a result of dehydration was not registered on site due to the above mentioned outage in measuring data. Otherwise, an even better level of compliance could have been expected.

## 5 CONCLUSIONS

The prescribed water balance model shows a good compliance between measured site data and the calculated efficiency of a GCL landfill liner system.

Due to ion exchange process all figures show only a slight decrease of system efficiency from 100 % during the first year to 99 % during the second and third year.

Both theoretical and empirial studies show a good performance of a needle-punched sodium bentonite GCL even if ion exchange and desiccation takes place. Therefore the model gives the chance to estimate and compare the sealing efficiency of different liner systems. It can be used to optimize system design parameters but it needs more field studies for evaluation.

## REFERENCES

Egloffstein T. A, 2000. *14th Geosynthetic Research Institute Conference, December 2000, Elsevier Science Ltd. 2001.* Natural bentonites – influence of the ion exchange and partial desiccation on permeability and self-healing capacity of bentonites used in GCLs

Krabbe, W., 1958. Mitteilungen der Hannoverschen Versuchsanstalt für Grundbau und Wasserbau, Technische Universität Hannover, Heft 13, Über die Schrumpfung bindiger

Böden, Eigenverlag

Madsen F. & Nüesch R., 1994. *Proceedings of an International Symposium Nürnberg, Germany, 14 – 15 April 1994, edited by R.M. Koerner; E. Gartung & H. Zanzinger "Geosynthetic Clay Liners"*, Characteristics and sealing effect of bentonites, AA. Balkema, Rotterdam, Bookfield 1995

Schnatmeyer, C., 1998. *Alternative Oberflächenabdichtungs- systeme für Halden und Altstandorte am Beispiel einer Gichtstaubdeponie.* Lehrstuhl für Geologie, Universität Trier

Siegmund, M. & Witt K. J. & Alexiew N., 2001. *Sonderheft dergeotechnik zur 7. Informations- und Vortragsveranstaltung über "Kunststoffe in der Geotechnik", München*, VGE VerlagGlückauf Essen 2001, Calcium-Bentnitmatten unter Feuchtigkeitsänderungen

US EPA, 1994. *The Hydrologic Evaluation of Landfill Performance (HELP) Model.* Engineering Documentation for Version 3. United States Environmental Protection Agency, Office of Research and Development, Washington, EPA/600IR-94/168b