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Investigation of bentonite requirements for geosynthetic clay barriers

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ABSTRACT: Since over 20 years Geosynthetic Clay Liners (GCLs) – according to the latest CEN TC189 definition Geosynthetic Clay Barriers (GBR-C) – have been successfully installed and used in many sealing applications. Research carried out by manufacturers, universities and other organizations have concentrated on several topics such as hydraulic conductivity, gas permeability, shear strength, performance of GCLs under changing conditions, i.e. freeze/thaw or dry/wet cycles, or damage during installation. This summary is only a part of the large list of issues investigated. After growing confidence for the sealing system GCLs are capable of substituting most compacted clay liners or sand/bentonite soils, GCLs were adopted in several regulations as a state-of-practice sealing element. A topic which has never been really investigated or published is the realistic minimum requirements of the GCL components. These include the geotextile components as well as the bentonite layer. This investigation, which covers a fundamental topic, was carried out due to the fact that several specifications appeared where extreme low mass per unit areas of bentonite were specified and designers and regulators questioned whether the GCL would function properly. This paper will concentrate and present data on the bentonite layer showing what the lowest mass per unit area of the bentonite layer must be to allow the GCL to achieve the usually quoted manufacturers hydraulic conductivity value of $<5 \cdot 10^{-11}$ m/s. Further the paper will present the expected long-term development with a mass per unit area that is located around the minimum acceptable value. Various bentonite types were tested and interesting differences between the bentonite types occurred during the investigation. It will allow the designer and specifier to specify a GCL with a lowest minimum mass per unit area of bentonite which will ensure that the GCL will perform as a sealing element without risk and allow conclusions on the long-term performance.

1 INTRODUCTION

Hundred millions of years ago, many parts of the world experienced extensive volcanic activity. During long periods of eruptions, immeasurable amounts of ash were disgorged and covered large areas all over the world. Over millions of years, the ash was repeatedly deposited and interbedded with eroded silts and sediments. Slowly, the glass component of the ash was chemically altered and consolidated into distinct layers of clay, often associated with Zeolite beds, marl, sandstone as well as shale and mudstone. As plate drift continued, areas were lifted and folded into mountains. Sea areas were drained and ash deposition subsided as the clay/silt formations were heaved upwards. These areas were eroded and weathered over time, exposing numerous clay beds of the "patents" or "claims" that are commercially mined today. The Black Hills and the Big Horn mountains in North America are two areas, where predominately natural sodium bentonite (Wyoming bentonite) is mined.

Sodium bentonite is mined via open pit methods and can require as much as four times the amount of overburden to be removed, compared to the thickness of the recoverable clay layers. Beds of bentonite can be as thin as several centimeters to as thick as several meters depending upon the volume of ash being deposited at the time, as well as the sea's currents that may have concentrated deposits. Deposits can be quite expansive, stretching for miles in many directions.

The term "Bentonite" is generally applied to the colloidal clays originally associated with the Cretaceous Benton Shale outcrops near Fort Benton, Wyoming. In the late 1880's, the "clay of a thousand uses" was first called Taylorite, after William Taylor; one of the first commercial producers of the product in the Rock River area. Finding that name already taken, the clay was renamed for the Benton formation in which the outcrop was found, i.e. Bentonite.

Table 1. Common GCL applications.

Application
Landfill lining systems
Landfill cover and capping systems
Secondary containment liners
Water reservoirs
Waterproofing systems
Environmental (groundwater) protection
Dams and dykes
Vertical barrier
Underwater installation

Sodium bentonite, often called "western" bentonite is characterized by having sodium as its predominant exchangeable ion. Sodium bentonite is not to be confused with Calcium bentonite, which has calcium as its predominant exchangeable ion.

Sodium bentonite is not itself a mineral name, but more correctly, it is a smectite clay composed primarily of the mineral Montmorillonite. Montmorillonite is a three layer mineral formed of several layers of tetrahedron and octahedron sheets, electrostatically held together by isomorphic interlayer cations. As the electrostatic attraction is low, exposure to polar fluids will cause the formation of a monomolecular lattice of water between the silicate layers. The basis behind bentonite swelling is that several layers of water dipoles can form into weak "stacked" tetrahedral structures, causing the silicate layers to separate – this is termed intercrystalline swelling.

Purity of sodium bentonite will vary, as the depositional environment and subsequent weathering processes also differ by region and deposit. While not necessarily a sign of a clay's quality for use in a Geosynthetic Clay Liner (GCL, or GBR-C according to the latest CEN terminology draft), the typical sodium bentonite used in a Geosynthetic Clay Liner product will contain 60–85% Montmorillonite.

As with any naturally occurring ore, bentonite deposits vary in their qualities. Statistical process control as well as thorough deposit surveying and analysis allows bentonite producers to minimize variability – ensuring consistent bentonite qualities in every product they deliver. While the commercially packaged form of sodium bentonite is either a fine powder or one of numerous granulations, the dispersed particle size of sodium bentonite is actually less than 2 microns.

Geosynthetic Clay Liners are manufactured hydraulic barriers consisting of high swelling clay bonded (natural sodium bentonite) to a layer or layers of geosynthetics. They are used mainly as a replacement of thick, difficult to build, compacted clay liners. Table 1 lists a partial overview of the more common applications.

Needlepunching is the most common method of forming a shear strength resistant GCL, due to the complex entanglement of the fibre reinforcement. The needlepunching technology allows to overcome the weak internal shear strength of bentonite (~8°) and manufacture a shear strength transferring GCL. Approx. 2.5 million needle-punched fibres per m^2 create a unique GCL with several important advantages:

- Long-term resistant bonding of encapsulating geotextiles
- Uniform and directional independent shear strength
- High internal shear strength transfer
- Encapsulation of bentonite, prevents displacement of bentonite
- Creates bentonite swelling pressure towards the bentonite pores

2 STANDARD BENTONITE TEST METHODS

The need of GCL standards is often underestimated in the industry. But if one looks deeper into the benefits of standards their value can easily be appreciated. The GCL manufacturer is able to test his product under given standards and quality control the different resin, bentonite and geosynthetic properties for the final GCL product and further check on manufacturing properties of the final GCL. With given quality control measurements the expected GCL properties are ensured as well as the uniformity of the GCL product. Designers and specifiers can require, respectively specify GCL properties and therefore secure the performance of the GCL in the application. The installer, owner and on-site inspector is able to perform acceptance tests and verify required properties and inspect whether the GCL is transported, stored and installed according to standard guides.

Various industry representatives are working as members in various standardization groups on the formulation of test methods, specifications, guides, practices, terminology, and the dissemination of knowledge dealing with GCLs. The formulation of test methods, specifications, guides, practices and terminology for GCLs is established in special committees and approved by the involved industry experts. With these activities the users of GCLs are provided with the appropriate test methods to ensure that index and performance tests can be carried out on GCLs. Standard guides outline procedures for the proper handling, storage and installing of GCLs as well as a guide for manufacturing quality control and acceptance testing. Application related standards give a guide for the proper tests for certain applications.

An overview of current GCL standards or standards which can be used for GCL testing are listed below:

2.1 *Bentonite properties*

- ASTM D5890 Standard Test Method for Swell Index of Clay Mineral Component of GCLs
- ASTM D5891 Standard Test Method for Fluid Loss of Clay Component of GCLs
- ASTM D6141 Standard Guide for Screening the Clay Portion of a GCL for Chemical Compatability to Liquids
- CUR 33 Montmorillonite Content by Methylene Blue Method
- DIN 18132 Enslin Neff

2.2 *GCL properties*

- ASTM D5887 Standard Test Method for Measuring of Index Flux through Saturated GCL Specimens Using a Flexible Wall Permeameter
- ASTM D 5889 Standard Practice for Manufacturing Quality Control of GCLs
- ASTM D5993 Standard Test Method for Measuring Mass Per Unit of GCLs
- ASTM D6243 Standard Test Method for Determining the Internal and Interface Shear Resistance of GCLs by the Direct Shear Method
- ASTM D6495 Test Method for Bonding Peel Strength of Needlepunched GCLs

2.3 *Site specific standards*

- ASTM D5888 Standard Guide for Storage and Handling of GCLs
- ASTM D6072 Standard Guide for Obtaining Samples of GCLs
- ASTM D6102 Standard Guide for Installation of GCLs
- ASTM D6495 Standard Guide for Acceptance Testing Requirements for GCLs

2.4 *Application related standards*

- prEN 13361 – Geosynthetic Barriers – Characteristics required for the use in the construction of reservoirs and dams
- prEN 13362 – Geosynthetic Barriers – Characteristics required for the use in the construction of canals
- prEN 13363 – Geosynthetic Barriers – Characteristics required for the use in the construction of tunnels and underground structures
- prEN 13492 – Geosynthetic Barriers – Characteristics required for the use in the construction of liquid waste disposal sites, transfer stations or secondary containment
- prEN 13493 – Geosynthetic Barriers – Characteristics required for the use in the construction of solid waste storage and disposal sites, and storages for hazardous solid materials

Looking at the bentonite specific standards, especially the ones quoted in ASTM D5889 “Standard Practice for Quality Control of GCLs” and ASTM D6495 “Standard Guide for Acceptance Testing Requirements for GCLs” it is obvious that only two test methods are frequently been asked as a quality control measurement. These are ASTM D5890 “Standard Test Method for Swell Index of Clay Mineral Component of GCLs” and ASTM D5891 “Standard Test Method for Fluid Loss of Clay Component of GCLs”. The ASTM test method D5887 “Standard Test Method for Measuring of Index Flux through Saturated GCL Specimens Using a Flexible Wall Permeameter” is a bentonite related test method but is mainly used on the finished GCL and not the bentonite property. Additionally the manufacturing process and the use of additives such as polymers and glues can positively affect the hydraulic permeability. It therefore is not considered as a test method to determine the bentonite quality as a quick and simple test procedure. However it is recommended to test the bentonite on its own if glues and additives are used.

Bentonite is the key component for a GCL. The function is to maintain a low hydraulic conductivity in the hydrated state. It is therefore understandable that the bentonite component undergoes a stringent quality control process before the bentonite is used for the production of the GCL. The following test procedures describe the state of the art bentonite testing used for GCLs. It must be understood that these tests are not stand-alone tests and in the GCL industry the result of one single test does not allow an interpretation of the bentonite. However taking all results together in account they allow a determination of an expected performance of the bentonite.

Sodium bentonite is commonly distinguished by its ability to swell several times its natural volume – when exposed to water. The test method used for quantifying the swelling property for use in GCLs is ASTM D5890 – Standard Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners. This index test is useful for establishing the relative quality of a clay for use in a GCL. The current industry standard is >24 ml.

For most environmental applications, sodium bentonite is also evaluated for use based upon its ability to create a seal. This test is ASTM D5891 – Standard Test Method for Fluid Loss of Clay Component of Geosynthetic Clay Liners. Many consider this index test to be a quick qualitative test, suggesting the bentonite's ability to work effectively in a GCL. The current industry standard is <18 ml.

While not critical for other applications of bentonite, the bentonite in a GCL must act as a hydraulic barrier. It is the high swelling properties that provide sodium bentonite's unique sealing qualities. As the clay hydrates and swells, the path for water to flow though becomes complex as the clay platelets intersperse. The most important test to evaluate the sealing qualities of bentonite in a GCL is a permeability or flux test. This test is ASTM D5887 – Standard Test Method for Measurement of Index Flux Through Saturated Geosynthetic Clay Liner Specimens Using a Flexible Wall Permeameter.

The Methylene Blue methodology describes how the absorption of a methylene blue solution is determined and gives a cation absorption value. The current ASTM standards C837 and D2330 are not considered to be suitable for the GCL industry. The German VDG P 96 Bestimmung des Methylenblau Wertes (Determination of the Methylene Blue Value) and the Dutch CUR Methyleenblauw-waare (Methylene Blue Values) method are mostly used and standard practice. This method is occasionally used by GCL manufacturers to determine the absorption capacity and the percentage of montmorillonite.

With an X-Ray Diffraction (XRD) the identification of mineral species and the quantitative estimation of their relative portions is possible but an exact quantification usually requires several complementary analyses. This method is occasionally used by GCL manufacturers to determine the montmorillonite content in the bentonite but i.e. the presence of non-swelling illite partially accounts for a discrepancy in results (higher montmorillonite content). This method is not applicable for GCL specifications, especially because there are no standardized test methods available and results, resp. interpretation can vary from testing person to testing person. However the method is applicable to fingerprint and identify mineral species within the bentonite.

An important value for a GCL is the mass per unit area of the bentonite. In earlier days the value was set at 4900 g/m^2 but it was not specified at which moisture content. This caused a bit confusion on the market because glued products, where water soluble glues were added to the bentonite to allow the bentonite to stick against the cover and carrier geotextiles, reduced the amount of bentonite in the product. The ASTM D5993 – Standard Test Method for Measuring Mass Per Unit of GCLs now describes that the mass per unit area of the bentonite is to be reported at a dry moisture content. Therefore the reported values determined after this method are all comparable with each other (with the exception of the "glue").

GCL manufacturers are ideally looking for one simple test which allows an interpretation, whether the supplied bentonite meets their bentonite criteria and acts as a long-term sealing barrier. To date the author is not aware of such single test. The current practice is to use several tests for bentonite identification but is currently limited to as few as two tests (Swell Index and Fluid Loss, according to ASTM D5889 "Standard Practice for Quality Control of GCLs"). Out of the authors experience a natural sodium bentonite which meets the five criteria in Table 2 will pass the maximum hydraulic conductivity of $<5 \cdot 10^{-11}$ m/s (according to ASTM D5887).

In cases in which the hydraulic conductivity value of $5 \cdot 10^{-11}$ m/s was not met at least one or more of the requirements in Table 2 were not achieved. However in single tests it was possible that a bentonite met the required hydraulic conductivity of $<5 \cdot 10^{-11}$ m/s (according to ASTM D5887) but did not meet the swell index or the Enslin Neff value. This fact reinforces even more the need to specify more than just two bentonite test methods, since the hydraulic conductivity is the most important requirement and is a long running test (usually >14 days) and is recommended to be tested once every week according to ASTM D5889 "Standard Practice for Manufacturing Quality Control of GCLs".

Table 2. Bentonite requirements for a natural sodium bentonite (hydraulic conductivity of $<5 \cdot 10^{-11}$ m/s).

Requirement	Standard	Value
Mass per unit area	ASTM D5993	>3,500 g/m^2 (@10% moisture content)
Swell Index	ASTM D5890	>24 ml
Fluid Loss	ASTM D5891	<18 ml
Enslin Neff	DIN 18132	>600%
Methylene Blue content	CUR 33	>300 mg/g

Table 3. Bentonite Properties after non-confining stress exposure on a subsoil.

Time	Test method	Wyoming bentonite	Na^+ activated bentonite
17 months	Enslin Neff/Swell Index	775%/35 ml	245%/8 ml
19 months	Enslin Neff/Swell Index	790%/34 ml	215%/7 ml
24 months	Enslin Neff/Swell Index	725%/32 ml	210%/2 ml
28 months	Enslin Neff/Swell Index	690%/30 ml	Not tested

Table 4. Bentonite properties of an exhumed (after 5 years of service) GCL.

	Fluid Loss	Swell Index	Hydraulic Conductivity
Original GCL	14 ml	32 ml	$2 \cdot 10^{-11}$ m/s
Exhumed GCL	11 ml	32–34 ml	$1.4–2.2 \cdot 10^{-11}$ m/s
	Potassium	Sodium	Calcium
Ion content of exhumed GCL	14 ppm	690 ppm	179 ppm

3 NATURAL SODIUM BENTONITE VERSUS SODIUM-ACTIVATED BENTONITE

In North America natural sodium bentonite (Wyoming bentonite) is most commonly used. In other parts of the world where GCLs are manufactured it occurs as a commercial disadvantage to use Wyoming bentonite so that next to Wyoming bentonite other natural sodium bentonites or sodium activated bentonites from closer deposits are used. Marginal quality bentonites are being mixed with soda ash (Na_2CO_3) in order to increase the quantity of exchangeable sodium. However soda ash treated calcium bentonites degrade considerably more than Wyoming sodium bentonites and tend to have poorer hydraulic conductivities (Alther 1987).

This fact was also determined in a simple test where two GCLs – one with 4900 g/m^2 Wyoming bentonite and one with 4,900 g/m^2 sodium activated bentonite – were exposed to the local North German weather conditions (Rudolph 1993). In both cases the GCLs were unconfined and there were no free cations from a cover soil available. The results in Table 3 show that the sodium-activated bentonite underwent an ionic exchange within less than 17 months, whereas the Wyoming bentonite did not show such a behavior after 28 months.

A recent published paper (Mansour 2001) describes a test trial where a GCL (single liner) covered with 0.66 m cover soil remained intact after a five year period under a soil with low calcium content. After over five years in service the bentonite had nearly the original properties (Table 4). This example shows clearly that a GCL can maintain its properties if designed properly and act as a single barrier with i.e. a minimum cover soil of at least 0.60 m. Additionally the top soil chemistry can help to let the GCL act as a long lasting stand alone barrier. In connection with a cover geomembrane the long-term performance of the GCL is out of question. With increasing cover soil thickness even a calcium rich soil, which can change the ionic properties of the sodium bentonite can positively affect the GCL performance. As with each liner system the design in most cases influences the performance, not necessarily the liner product.

Heerten (2002) summarizes in his paper several more positive test plots with natural sodium bentonite GCLs, where the efficiency of stand alone GCL liners are published. Each of these cases were designed with a minimum cover soil thickness of 0.75 m and proves that the GCL outperforms similar designs with compacted clay liners.

Table 5. Tests with a Na^+-activated and natural sodium bentonite based on a landfill base seal application.

	GCL A	GCL B (needlepunched)
Bentonite	Sodium (Na^+) activated	Natural sodium (Na^+)
Final hydraulic conductivity	1.62 and $1.39 \cdot 10^{-10}$ m/s	3.17 and $2.7 \cdot 10^{-11}$ m/s
Na^+ montmorillonite	59%	81%
Enslin Neff water absorption	215%	445%
Chloride break-through time	41 days (1.5 months)	420 days (14 months)
Chloride transport	Less effective	Good
Wet/dry behaviour	Less favourable	Good
Freeze/thaw behaviour	Less favourable	Good

Szabó & Balázs (2000) published some data on two different European manufactured GCLs – GCL A a product where the sodium activated bentonite is filled into a woven/nonwoven composite carrier and the carrier geotextile being thermally attached to the carrier fibres and GCL B a needlepunched product with natural sodium bentonite. The tests were selected to simulate landfill base seal conditions and are summarised in Table 5.

It is obvious that the tested bentonites showed some severe differences in the testing performance and the conclusion could be drawn that the use of the specific tested bentonite is not necessarily suitible for a sealing application, especially if a long-term hydraulic conductivity of $1 \cdot 10^{-10}$ m/s is required.

That there are some significant differences in the bentonite qualities of activated bentonite was already recognised during the production of needlepunched GCLs with activated bentonites prior to 1994. Since the invention of needlepunched GCLs in 1987 Naue Fasertechnik established a quality control test which investigated the sealing performance of the GCL over the entire production width. A 1 m long sample of the entire GCL width was clamped in an open frame so that it formed a tub. It was then filled with water and after a period of several hours the bottom side was checked. In a dry case it was obvious that the GCL acted as a seal. In cases of wet spots the whole production lot underwent a stringent quality control procedure as well as the bentonite. In all cases before 1994 where wet spots were observed the bentonite properties of the activated bentonites did not meet the bentonite requirements and were not fully sodium activated, therefore showing higher hydraulic conductivities. In 1994 Naue Fasertechnik began using natural sodium bentonites and in those cases never again observed wet spots in this easy, but sufficient, to carry out test.

Based on the findings summarised in Tables 3 and 5 further investigations concerning the differences of natural sodium bentonite and activated sodium bentonites were carried out. At first a simple clay mineral chemistry analysis was carried out comparing the main bentonites with each other. For this reason a natural Wyoming bentonite, a Greek sodium activated bentonite as well as a calcium bentonite were investigated (analysis in Table 6). All of these bentonites have been used in GCLs, however if a calcium bentonite is used the minimum mass per unit area of bentonite should be approx. 10,000 g/m² if permeability values of approx. $1 \cdot 10^{-10}$ m/s are to be ensured. On the other hand such GCLs are limited in roll lengths and difficult to handle on site. Tests from Egloffstein (2001) have shown that a 8,000 g/m² heavy GCL with calcium bentonite does not perform better than a GCL with 4,000 g/m² natural sodium bentonite and then ionic exchanged. Further the natural sodium bentonite has the high swelling capacity during the first project stage, such as installation and the settlement period and can therefore heal any likely defects, such possibly occurring during installation, placement of the cover soil and the settlement phase. A calcium based GCL however would show a lack of self healing due to the very low swelling capacity of the bentonite.

The chemical analysis shows one important fact. First of all based on the amount of CaO it can be identified that both the calcium bentonite as well as the sodium activated calcium bentonite still contain a larger amount of Calcium (CaO). This means that the natural sodium bentonite has more sodium and less calcium ions on the outer bentonite flake surface. Due to the soda ash treatment of the activated bentonite only calcium from the bonding of the negative charged surface is replaced but not the calcium between the bentonite. In cases where the activated bentonite contains a high amount of Na_2O there is an indication of soda ash treatment but this is only an indication.

In the case of soda ash activation one would not describe such a bentonite as a natural sodium bentonite. Ongoing research is further investigating how to determine if a bentonite has been soda ash treated or not, since the concept is to use a natural sodium bentonite, due to the described better performance and the better uniformity of the bentonite in terms of sodium distribution.

The soda ash activation process of calcium bentonites (and even natural sodium bentonites of lower quality) takes place in field where soda ash is mixed by means of vehicles driving over the raw bentonite and mixing the

Table 6. Chemical analysis of typical bentonites used for GCLs.

Clay mineral chemistry:		Corrected for Quartz and Opal	
Bentonite: Source:	Wyoming USA	Na^+ activated Germany	Calcium Germany
Chemistry as analyzed: (Corrected to moisture free basis and normalized)			
% SiO_2	61.12	54.50	49.09
% Al_2O_3	20.82	18.41	20.44
% Fe_2O_3	4.35	5.84	5.85
% MnO	0.02	0.04	0.04
% MgO	2.50	3.89	5.27
% Na_2O	2.50	2.46	0.55
% K_2O	0.56	1.64	1.99
% CaO	1.48	3.15	3.83
% TiO_2	0.16	0.44	0.49
% P_2O_5	0.06	0.09	0.10
%C (in LOI)	0.43	0.96	0.77
% S (in LOI)	0.16	0.01	0.00
% LOI @ 105°C	6.43	9.55	12.37
Moisture Free Total:	100.00	100.00	100.00

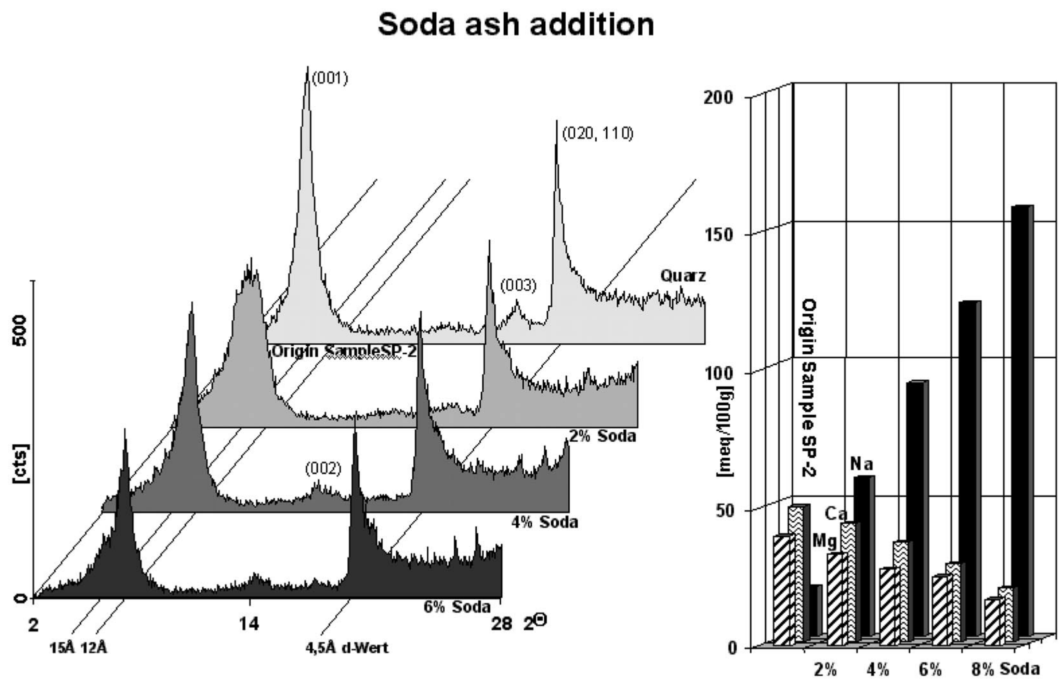

Figure 1. Distribution of Na, Ca and Mg in a soda ash activated calcium bentonite (Ibeco 2001).

specified amount of soda ash into the bentonite. The uniformity of the final bentonite is very much dependent on the amount of soda ash that is added. As described earlier non-exchanged areas can create high permeable areas. The right side graphic of Figure 1 shows clearly that there is a significant difference in the amount of sodium (Na^+) in the bentonite after addition of 2% to 8% soda ash to the calcium bentonite. The left XRD analysis does not show a significant difference in the XRD analysis of the activated bentonites and reinforces the fact that the XRD method is more likely to be unsuitable for fingerprinting the bentonite and allowing an interpretation between an activated and natural sodium bentonite.

Since the mass per unit area of bentonite is also an important GCL parameter and may be influenced by the bentonite quality further tests with natural sodium bentonite and sodium activated bentonites were carried out. The natural sodium bentonites ranged with the swell index value between 24 to 35 ml and with the Enslin Neff value between 630 and 835%. The sodium activated bentonites had swell index values between 22 and 29 ml and Enslin Neff values between 515 and 615%.

The hydraulic conductivities were carried out according to ASTM D5887, but are reported as permeability values in m/s, based on 1 cm thickness. Table 7 summarises the hydraulic conductivity results as a relation to mass/unit area of bentonite in the as delivered state (approx. 8–12% moisture content). The results allow the conclusion that in theory a GCL with natural sodium bentonite can be manufactured with as much as approx. 2700 g/m^2 bentonite, however with a sodium activated bentonite at least 3700 g/m^2 bentonite is needed to achieve a hydraulic conductivity of $5 \cdot 10^{-11}$ m/s. It must be understood that these minimum mass per unit area values are based on single tests. Depending on the manufacturing process about 10 to 20% more bentonite must be added to guarantee such a minimum average value.

Considering the minimum mass per unit area of 3500 g/m^2 for natural sodium bentonite from Table 2, a natural sodium bentonite will still act as a seal with well distributed minimum 2700 g/m^2 but one would give away all possible safety factors. It is therefore not recommended to specify a GCL with a natural sodium bentonite with less than 3500 g/m^2.

On the other hand one must require different minimum values for a GCL with sodium activated bentonite. Considering just the mass per unit area of the bentonite a recommended minimum mass per unit area for sodium activated bentonite should be at least 4500 g/m^2 or 1.3 times the mass per unit area of a natural sodium bentonite. Additionally in any case the other bentonite specific properties of Table 2 have to be fulfilled as well.

4 SUMMARY

Geosynthetic Clay Liners (GCLs) have proven to be an equivalent alternative to compacted clay liners and can be used as stand alone liners if properly designed. With a minimum of 0.6 m calcium poor cover soil thickness or a 0.75 m thick layer the GCL with a natural sodium bentonite will act as a long lasting barrier, if minimum bentonite requirements are fulfilled. These are summarized in Table 8.

In cases where sodium activated bentonites are used it is recommended to increase the minimum bentonite mass per unit area to 4500 g/m^2 or at least 30% more the amount of a natural sodium bentonite and still requiring

Table 7. Hydraulic conductivity values of GCLs with differing amounts of powder bentonite.

Bentonite mass per unit area [g/m^2] as delivered	Hydraulic conductivity [m/s]	
	Natural sodium bentonite	Sodium activated bentonite
5,100	$1.2 \cdot 10^{-11}$	
4,800	$1.5 \cdot 10^{-11}$	$1.7 \cdot 10^{-11}$
4,100	$1.6 \cdot 10^{-11}$	$2.0 \cdot 10^{-11}$
3,500	$1.7 \cdot 10^{-11}$	$2.6 \cdot 10^{-11}$
3,200	$1.9 \cdot 10^{-11}$	$6.0 \cdot 10^{-10}$
2,700	$2.8 \cdot 10^{-11}$	$1.5 \cdot 10^{-9}$

Table 8. Minimum bentonite requirements.

Properties	Test methods	Minimum values
Mass per unit area	ASTM D5993	>3,500 g/m^2
Swell Index	ASTM D5890	>24 ml
Fluid Loss	ASTM D5891	<18 ml
Enslin Neff	DIN	>600%
Methylene Blue content	CUR	>300 mg/g

the above mentioned bentonite values. Additionally the manufacturing quality control and on-site quality control program should be increased if activated bentonites are being used.

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