CETCO
LINING TECHNOLOGIES
800.527.9948 www.cetco.com

1500 W. Shure Dr. Arlington Heights, Illinois 60004 USA
Phone: +1-847-392-5800 • Fax: +1-847-506-6150
www.cetco.com

Xcel Energy Sherco Pond

GCL Performance Study

September 2003

William Urchik
Project Engineer
CETCO

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Final Report

To: Steve Bluhm

Re: Xcel Energy – Sherco Pond

From: Bill Urchik

Fax: 847-506-6150
Ph: 800-527-9948

Company: CETCO

No. Pages: 6

Date: September 5, 2003

Dear Steve,

Please accept this final report to address questions raised by Don Kriens of the MPCA with regards to the testing procedures used to determine the performance of Bentomat with water from the Xcel Energy Sherco Pond. The proposed function of Bentomat in the liner system at this facility is to seal potential holes in the overlying geomembrane to minimize leakage in the liner system. CETCO understands that there is concern regarding the compatibility of Bentomat with the effluent being contained in the pond. Specifically, the MPCA is concerned about ion exchange and the effects that this may have on the sealing ability of Bentomat.

This report will address the parameters used in the performance testing program by J & L laboratories. Using this test data, the expected leakage through the liner system will be quantified using the Giroud and Bonaparte analysis for leakage through composite liner systems. This analysis is widely accepted in the waste containment industry and is also supported by an EPA study incorporating 287 landfill cells over a 10 year period. Lastly, CETCO will address the concerns regarding bentonite ion exchange in Bentomat with a thorough review of the latest research regarding ion exchange.

Performance Test Results

CETCO provided a sample of Bentomat ST to J & L laboratory for independent third party hydraulic conductivity testing with samples of Sherco pond water and landfill leachate supplied by Xcel Energy. The testing was conducted in accordance with ASTM D 5887. The results of the performance testing program were excellent for both the landfill leachate and the Sherco pond water. Both samples of GCL were tested for performance for well over 30 days in which the hydraulic conductivity of the GCL specimens stabilized at a consistent value. Bentomat ST had a hydraulic conductivity of 1.1×10^{-10} cm/sec with the Sherco Pond water and 3.1×10^{-10} cm/sec with the landfill leachate. Both performance test results are well below the CETCO certified hydraulic conductivity of 5×10^{-9} cm/sec indicating that GCL is compatible with the leachate and pond water.

ASTM D6766-12

Compatibility Test Parameters

ASTM D 5887 uses an effective confining pressure of 4psi. This is the difference between the cell pressure and the average of the head and tail pressure. Theoretically this represents the minimum pressure required to prevent side wall leakage between the GCL and the membrane when performing hydraulic conductivity testing. If we were to increase the head pressure to model site specific conditions for a hydraulic head of 68 feet, the effective confining stress would be increased and the hydraulic conductivity of the GCL would be lower for the reasons described above. For example consider the following:

68 feet hydraulic head
1psi – 2.307 feet of water
GCL = 0.25 inches thick

$$\text{Required Gradient} = \frac{68 \text{ feet x } 12 \text{ inches/foot} + 0.25\text{inches}}{0.25 \text{ inches}}$$

$$= 3265$$

Converting required gradient into psi for flexible wall permeameter testing

$$\frac{68 \text{ feet}}{2.307 \text{ feet/psi}}$$

= 29.5psi ~ This is the required bias pressure to achieve a gradient of 3265 across the GCL specimen. To achieve this gradient we could set the tail pressure at 10psi and the head pressure at 39.5psi. However to prevent the membrane encapsulating the GCL from expanding, the cell pressure or confining pressure must be greater than 39.5 psi. To guard against pressure fluctuations we can set the cell pressure at 42psi. However, with this set-up we now have the following effective stress conditions:

$$42\text{psi}-\{(39.5\text{psi} + 10\text{psi})/2\} = 17.25 \text{ psi}$$

As the above calculation shows, the effective confining stress is greater than what is expected in the field, where a hole in the overlying geomembrane may exist. As a result the hydraulic conductivity of the GCL will be significantly lower because the effective stress was inadvertently increased. If a confining pressure of approximately 20psi were used, the resulting hydraulic conductivity would be approximately 1 to 1.5 orders of magnitude lower than the test results reported by J&L. Based on this fact, the hydraulic conductivity of Bentomat ST, tested at an effective confining pressure of 4psi and gradient of 220.8 is conservative.

Pond Depth

CETCO was not aware of the pond depth when the testing was initiated with J&L laboratory. However, testing GCL in a flexible wall permeameter per ASTM D 5887 requires a cell pressure of 80psi with a back pressure of 75psi and a head pressure of 77psi. The results in a confining pressure of 4psi (80psi-(77psi+75psi/2)). This confining pressure is necessary to eliminate sidewall leakage of permeant around the sides of the GCL or between the GCL and the membrane. Please refer to tab 2 for a schematic of the GCL hydraulic conductivity test set-up as performed by J&L laboratories. As mentioned, the effective pond depth is 68 feet and with a GCL thickness of 0.25inches the in-situ gradient would be in the order of 3238, which is unitless. However, the gradient used in the testing was 220.8. This is a function of the head pressure and the thickness of the GCL. While it is possible to test the GCL for hydraulic conductivity at a higher gradient, it is not possible to perform this testing without changing the confining pressure. With GCL's, the hydraulic conductivity is inversely proportional to the confining pressure. In other words, as the confining pressure increases the hydraulic conductivity decreases. This is a well known and accepted phenomenon with GCLs. In landfill applications, the performance of the GCL will increase as the landfill cell is filled. Please refer to tab 3, which is independent research demonstrating this phenomenon. Also shown below is a plot of hydraulic conductivity vs. confining pressure from research conducted by David Daniel of the University of Illinois. This data demonstrates that when a GCL is permeated with a very aggressive solution, $CaCl_2$ in this case and the GCL has the opportunity to experience complete cation exchange under low confining pressure, the GCL will retain its original hydraulic conductivity of 5x10^{-9} cm/sec when the confining pressure reaches 40 psi. Please refer to CETCO TR-321 for a detailed analysis (tab 4). This test data also represents a "worst case" situation as the GCL was not allowed to hydrate with water as would happen in real-world applications.

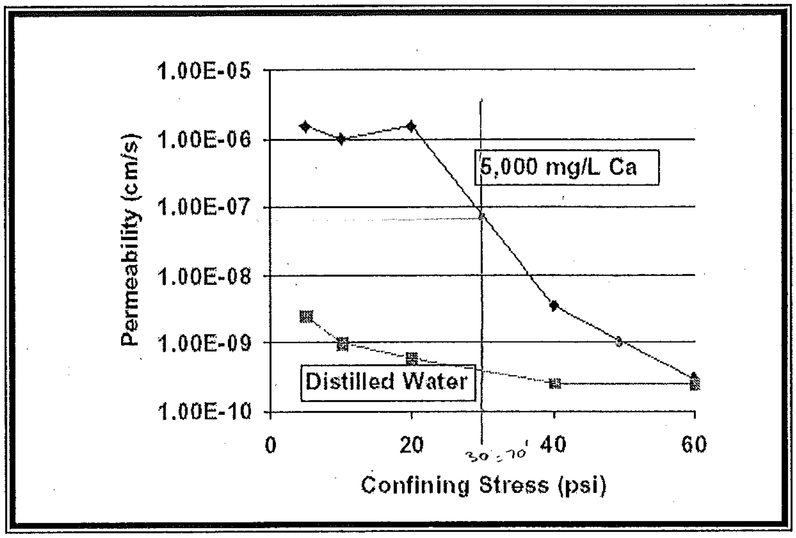


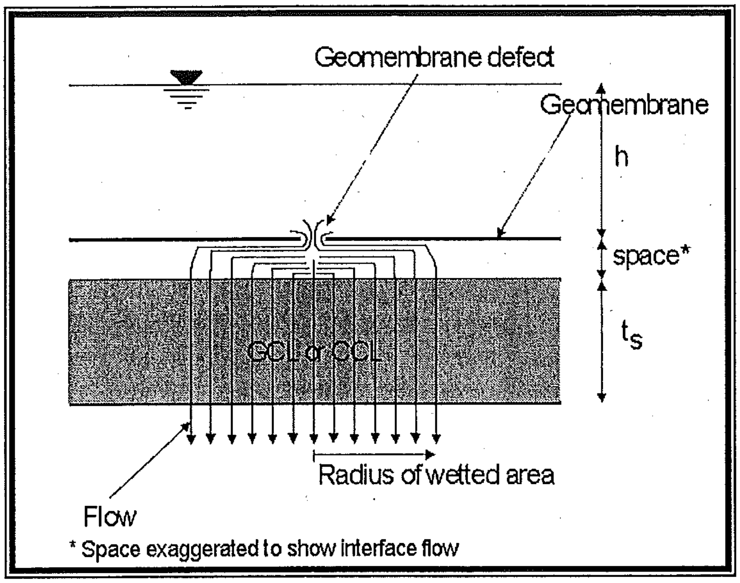
Figure 1. Daniel 2002 – University of Illinois

Performance of Composite Liner Systems

To evaluate the performance of a composite liner systems subjected to site specific conditions, we must consider the following approach provided by Giroud and Bonaparte. This is widely accepted in the lining and waste containment industry. The performance of a composite liner system is to quantify leakage through potential defects in the overlying HDPE. With good CQC/CQA procedures during construction, these defects can be kept to a minimum. A conservative analysis performed by many composite liner system designers, is to assume one 1.0 cm diameter hole per acre. Using the geometry of the assumed defect in the overlying HDPE, the Giroud and Bonaparte analysis will be applied to calculate the leakage through this defect in the HDPE. As the constituents in the pond may degrade the swelling capability of the bentonite in the GCL, we will consider the GCL to have a varying hydraulic conductivity. For this analysis, we will assume the GCL to have a maximum hydraulic conductivity of 3 x 10^{-8} cm/sec. This is over 2 orders of magnitude increase in hydraulic conductivity of Bentomat from the laboratory test data and is estimated to worst case and unlikely.

GCL Hydraulic Conductivity with Lime Sludge Leachate	***Comments***	***Likelihood***
1x10^{-10} cm/sec	Performance of GCL with leachate having no effect. Using test data from hydraulic conductivity testing with pond water	Possible
1x10^{-9} cm/sec	Performance of GCL with leachate having some effect on bentonite swelling. This hydraulic conductivity is greater than the tested value with pond water	Probable
3x10^{-8} cm/sec	Performance of GCL with leachate having significant effect on bentonite swelling.	Unlikely

A schematic of the analysis is provided below:



The rate of leakage through a geomembrane liner due to geomembrane permeability is negligible compared to the rate of leakage through defects in the geomembrane (Giroud and Bonaparte 1989.) Hence, only leakage through defects will be considered. If there is a defect in the geomembrane, the liquid first passes through the defect, then it flows laterally some distance between the geomembrane and the low-permeability soil, and, finally it infiltrates in the low permeability soil. Flow between geomembrane and low-permeability soil is called interface flow, and is highly dependent upon the quality of contact between the two components (Bonaparte et al., 1989.) Contact conditions are defined as follows:

Problem Parameters:

Project Maximum Leachate Head: 20.7m (68 feet)
GCL Thickness: 0.007m (0.021 feet)
Geomembrane Defect: 0.01m (1 cm)
Area: 4046m^2 (43,528.5 ft^2) 1 acre
Defect: 1cm diameter

Performing the calculation reveals the following expected leakage rates:

GCL Hydraulic Conductivity	*Expected Leakage(gal/acre/day)*
1 x 10^{-10} cm/sec	7.39
1 x 10^{-9} cm/sec	40.61
3 x 10^{-8} cm/sec**	500

** Theoretical maximum hydraulic conductivity of GCL, required to allow leakage of 500 gal/acre/day.

Many states conform to the "10 State Standard" allowing a leakage of 500 gal/acre/day. As demonstrated above the composite liner system incorporating a GCL can experience an increase in hydraulic conductivity of over two orders of magnitude and still perform within the requirements of the 10 state standard. The compatibility testing performed with the Sherco pond water resulted in a hydraulic conductivity of 1.1 x 10^{-10} cm/sec. Using this value in the Giroud and Bonaparte analysis, the expected leakage of the liner system is only 7.39 gal/acre/day. This is excellent performance.

Ion Exchange

Ion exchange is the process where a bivalent Ca 2+ ion exchanges a monovalent Na + ion in the structure of sodium bentonite. This results in a decrease in the bentonite swelling capability, and sometimes is accompanied with an increase in GCL hydraulic conductivity. However, research has concluded that certain conditions must exist for cation exchange to take place. Laboratory tests carried out by Lin and Benson (2000), (tab8) were performed with extreme wet – dry cycles which desiccated the bentonite. The GCL samples in this study were air dried with no confining pressure. These conditions exceeded in-situ conditions and cannot be considered to replicate in-situ performance. Egloffstein (2002), (tab 8) states that the increase in hydraulic conductivity noted by Lin & Benson is a direct function of the desiccation cracks as a result of air drying with the ion exchange having only an indirect influence. Egloffstein further states ***"Only when ion exchange and simultaneous desiccation of the bentonite are combined significant increases in permeability will result".***

The Xcel Energy Sherco pond project proposes a liner system incorporating a GCL covered with a Geomembrane. Such a system will not be subjected to wet - dry cycles where ion exchange can occur along with the damaging wet dry cycling. In effect, cation exchange should be of no concern for this project because of the overlying HDPE liner. While there is potential for cation exchange to occur where a defect in the HDPE liner may happen, conditions will not be present for a large increase in hydraulic conductivity as demonstrated in the Lin and Benson work. Bentomat will not be subject to wet dry cycling. Furthermore, a recent paper presented this past June in Denver at the ASTM symposium on GCL's showed that a GCL only cover system in a landfill had undergone ion exchange. Hydraulic Conductivity testing performed on GCL specimens indicated an increase in the GCL hydraulic conductivity. Free swell testing conducted on the bentonite per ASTM D 5890, indicated a substantial decrease the swelling capability of the bentonite. However, hydraulic conductivity testing performed on a sample of GCL covered with 30 inches of cover soil resulted in essentially the same hydraulic conductivity as the certified value of the GCL. This indicates that a cover soil of approximately 30 inches will keep the GCL in a hydrated condition and not allow desiccation cracks to occur which in turn can lead to an increase in hydraulic conductivity when occurring in conjunction with ion exchange. Lastly, Benson states ***"The safest approach is to cover the GCL with a geomembrane (ie., as in a composite barrier), and to ensure that sufficient surcharge overburden is placed above the geomembrane and GCL to maintain good interfacial contact".*** This is exactly the proposed configuration of the Xcel Energy Sherco pond liner system. The force exerted on the intact geomembrane by 68 feet of hydraulic pressure will result in significant overburden stress on the geomembrane GCL composite liner, providing excellent intimate contact creating little chance for cation exchange to occur. Furthermore, when Bentomat is covered by geomembrane, there is no opportunity for wet dry cycling which assures that the GCL will always be hydrated.

Hydration

CETCO has prepared a technical reference detailing how hydration of a GCL will occur in the field. CETCO TR-222, (tab 5) is a summary of an EPA workshop from 1995 detailing the hydration mechanism of GCL's against subgrade soils. This study shows that GCL's will hydrate from the subgrade even if the soil is in dry condition. A study presented at the ASTM symposium on GCL's in June 2003, (not yet published) indicates that GCL's in composite landfill liners remain hydrated for many years after cell construction and are expected to remain hydrated. Furthermore, water has the ability to diffuse through intact HDPE geomembrane and the potential difference in the water content above the liner vs. the water content in the soil below the liner, will continue to keep the GCL hydrated. There will be a constant driving mechanism forcing water from above the liner to below the liner via diffusion or water vapor transmission. In summary, short term and long term hydration of the GCL is not an issue.

Landfill Performance

CETCO understands that this wastewater pond will eventually be closed and made into a landfill cell. The US EPA has been studying the performance of landfill liner systems for the past 10 years on 91 landfills with 287 individual landfill cells. Data has indicated the superior performance of GM/GCL barrier systems over that of GM/CCL barrier systems. Incorporating a GCL in place of compacted clay in this liner system is expected to give superior performance in both the pond phase and the landfill phase of the project. Please refer to CETCO TR-316 (tab 6) for a detailed summary of the US EPA test data.

Conclusion

Performance testing of Bentomat ST with the Sherco pond and landfill leachate confirmed the performance of Bentomat to be acceptable with these fluids. Additionally, CETCO has provided two recent publications explaining that the effects of cation exchange on bentonite will not affect the performance of Bentomat for this project. The configuration of the proposed Xcel Energy pond liner with a HDPE geomembrane placed over top of Bentomat ST will offer Bentomat a number of additional benefits allowing it to perform as an excellent barrier for the Xcel Energy Sherco pond facility. The HDPE geomembrane will exert significant confining pressure on Bentomat as a result of the hydrostatic pressure acting on the geomembrane. This will cause the hydraulic conductivity of Bentomat to be less than the value achieved during performance testing. The in-situ performance of Bentomat will in effect be better provided a sound installation is performed. The geomembrane will also prevent wet-dry cycling of the GCL. This eliminates desiccation of the GCL, thereby minimizing potential increases in hydraulic conductivity from cation exchange due to wet dry cycling.

In summary, Bentomat ST was determined to have excellent performance with the pond water and the leachate and when used in conjunction with the HDPE geomembrane, the liner system will be an excellent barrier system for the Xcel Energy facility.

Should these responses require further explanation or clarification, please do not hesitate to contact me at 1-800-527-9948 x 7939.

Best Regards,

Wm Urchik

William Urchik
Project Engineer
CETCO
bill.urchik@cetco.com

GCL SAMPLE PREPARATION PROCEDURES

for

Hydraulic Conductivity - ASTM D-5084

and

Index Flux - ASTM D-5887

as performed by:

JLT Laboratories, Inc.
938 S. Central Avenue
Canonsburg, Pennsylvania 15317

December 2001
Revision March, 2002

GCL SAMPLE
PREPARATION PROCEDURES

extracts from

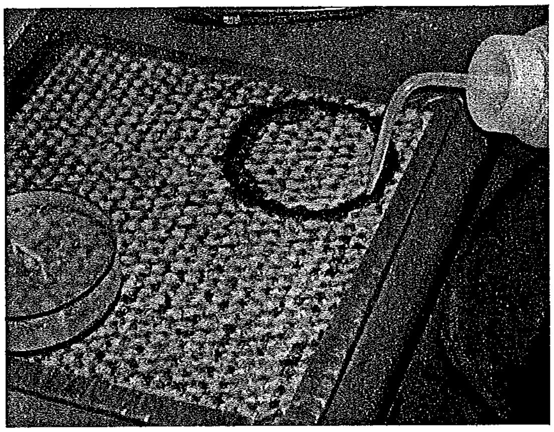
JLT Laboratories, Inc.

QUALITY MANUAL
for
GEOSYNTHETICS LABORATORY
Volume II
Procedures for
ASTM D-5084 and ASTM D-5887

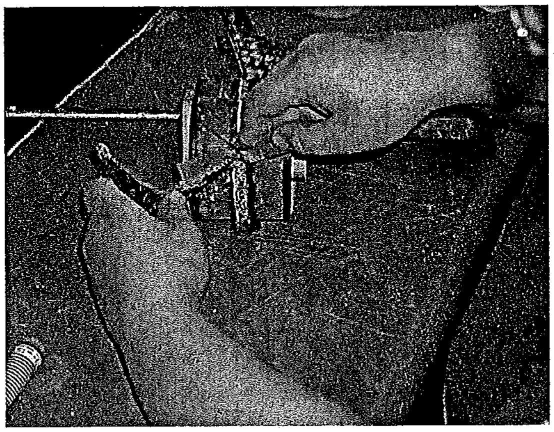
Last Revision
March 2002

938 S. Central Ave.
Canonsburg, Pennsylvania 15317
Tel: 724-746-4441
Fax: 724-745-4261
e-mail: jltest@cobweb.net

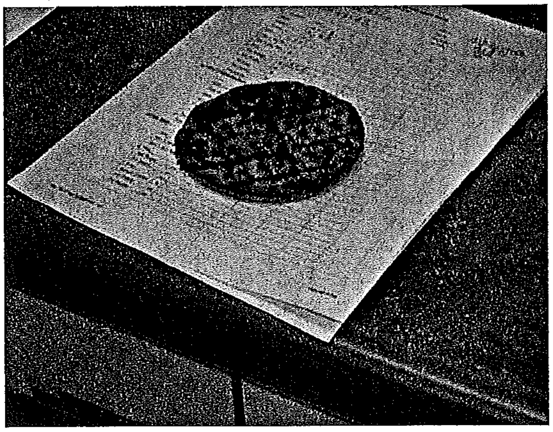
GCL SAMPLE PREPARATION SEQUENCE



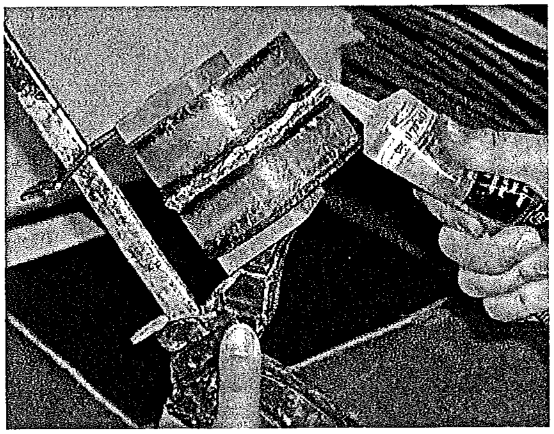
1. Trace specimen with a template and wet the edge to moisten the Bentonite. This holds the Bentonite in place when the specimen is cut unless otherwise specified by the client. *For Example: CETCO CRC products are not moistened prior to cutting specimen and must be trimmed in the humid room to prevent moisture loss.*



2. Clasp between a mold and, using a razor blade, cut the specimen to size.



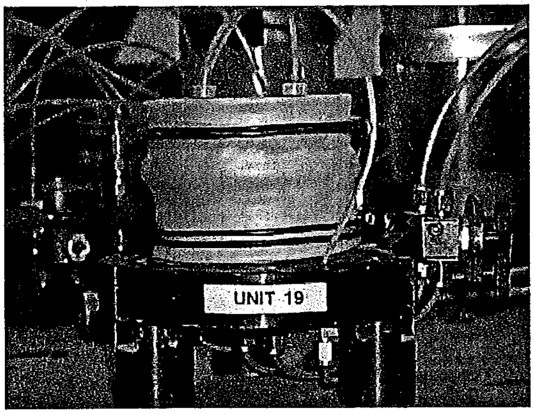
3. Weigh and record weight of specimen. Also determine the thickness of the Bentonite layer.



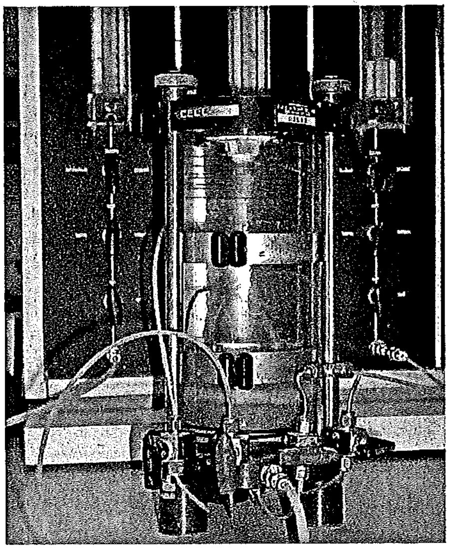
4. Seal the edge of the specimen with Silicone and allow to dry until the surface is dry but the interior is still soft.

JLT *JLT Laboratories, Inc.*

5. Install in triaxial cell and assemble per ASTM criteria



6. Apply the membrane and O-rings to seal the specimen



7. Assemble and fill Triaxial Cell, apply pressures and flush stones to evacuate excess air.

8. Perform test as specified by ASTM or Client criteria

SYSTEM CONFIGURATION for 4 inch Diameter GCL Specimens

ASTM D-5084/D-5887/EPA 9100

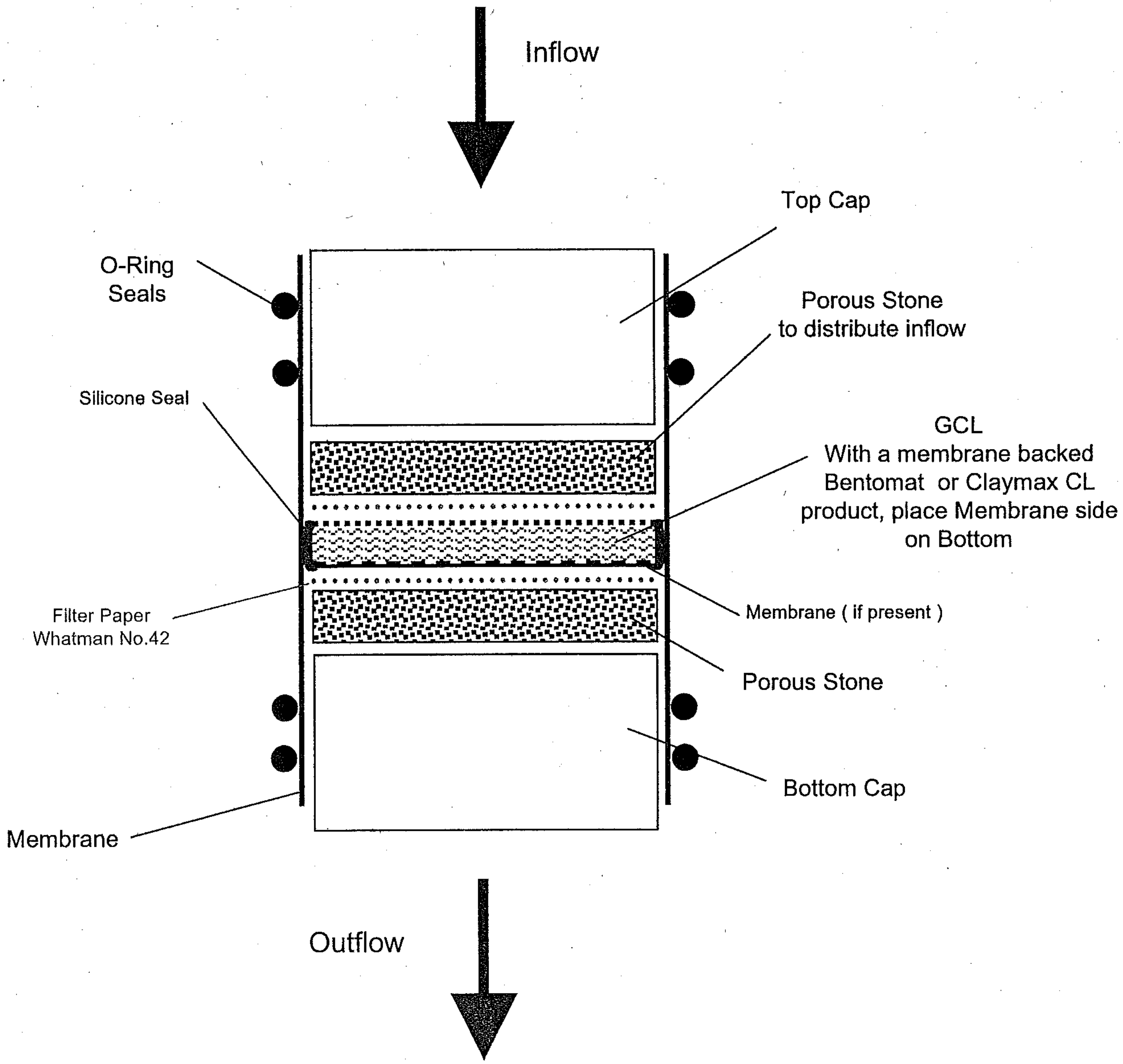
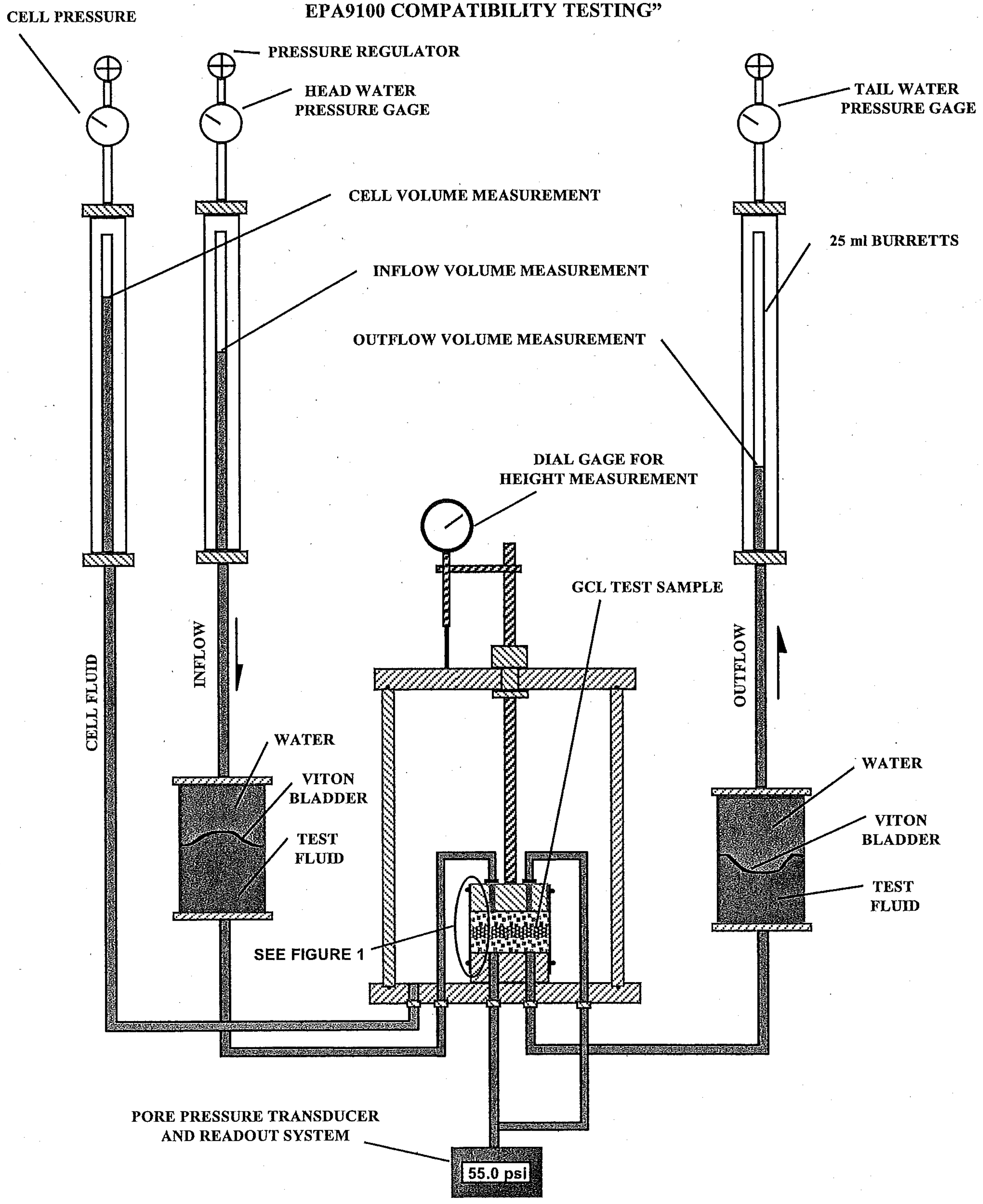


FIGURE 1

JLT *JLT Laboratories, Inc.*

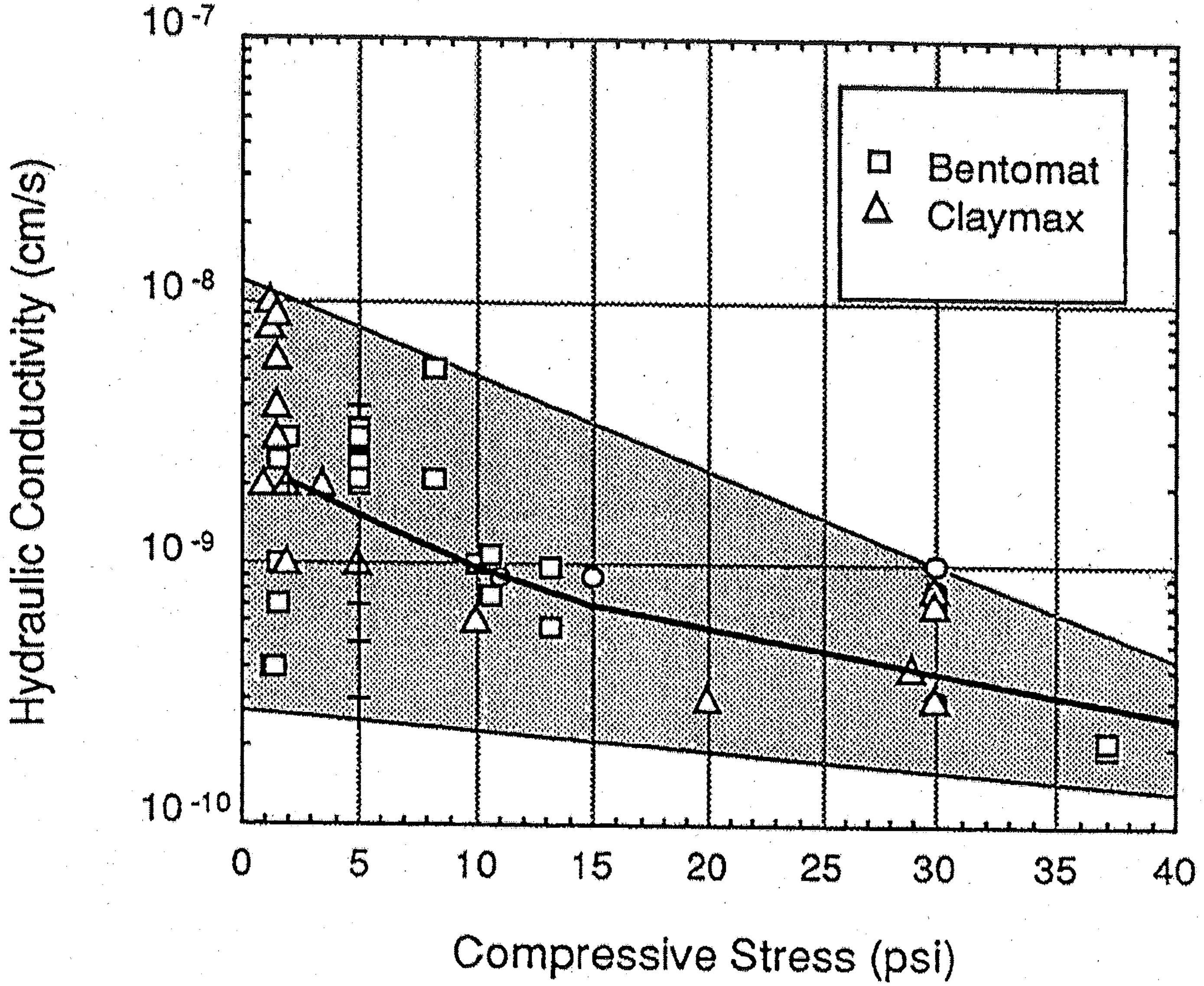
gclseal.ppt/c

FLEX-WALL TEST SCHEMATIC FOR GCL PERMEABILITY AND HYDRAULIC FLUX TESTING " ASTM D-5084 and D-5887 TEST PROCEDURES and EPA9100 COMPATIBILITY TESTING"



JLT Laboratories, Inc.
TXGCLCMP.PPT

FIGURE 2


Hydraulic Conductivity (cm/s)
10 -7
10 -8
10 -9
10 -10
0
5
10
15
20
25
30
35
40
Compressive Stress (psi)
□ Bentomat
△ Claymax

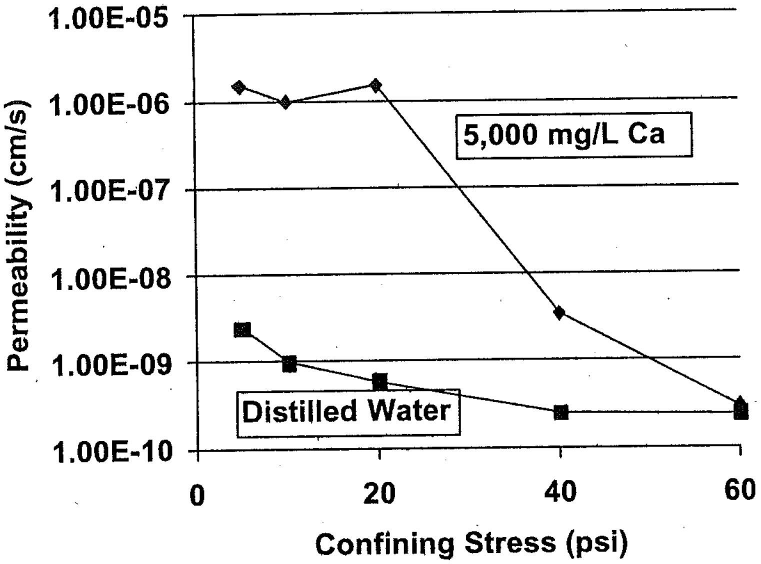
GCL PERFORMANCE IN A CONCENTRATED CALCIUM SOLUTION

Permeability vs. Confining Stress

The following test data was developed by Daniel in 2000 and published in the reference listed below. However, unpublished details about the testing, including this graph, were provided to CETCO in separate correspondences from Daniel. The purpose of this summary is to present all the data and information about the test program in one document.

The graph compares the effects of confining stress on the permeability of GCLs permeated with both water and a concentrated calcium chloride ($CaCl_2$) solution. The graph demonstrates that even when a highly contaminated liquid is permeated through a GCL, it still maintains an acceptable permeability of 5 x 10^{-9} cm/sec when the confining stress exceeds 40 psi or 275 kPa. Based on this data, Daniel concluded that, "chemical attack is of much less concern for a landfill liner than for a landfill cover." In other words, the high confining stress environment of a landfill bottom liner protects the GCL from permeability increases observed in low confining stress environments such as landfill final covers.

Test specimens were set up in flexible-wall permeameters, subjected to the final confining pressure, and then hydrated and subsequently permeated with either distilled water or a calcium chloride solution. For the calcium chloride tests, both the hydration liquid and the permeation liquid were the same calcium chloride solution. This solution was 13,700 mg/L $CaCl_2$, which is equal to 5,000 mg/L Ca^{++}. This liquid is believed to represent worst-case conditions in that the concentration was very high, and no fresh water permeation was allowed as would typically occur in real-world applications when the GCL is placed on a soil subgrade. Specimens were permeated for 10 pore volumes of flow, which was more than enough to achieve full ion exchange and equilibrium conditions.



The data shows that the decrease in permeability with increasing confining stress is even more dramatic than when fresh water is used as the permeant. Even in a highly contaminated liquid such as this, however, the GCL still functioned effectively when the confining stress reached approximately 40 psi (275 kPa).

References:

Daniel, D.E. (2000), "Hydraulic Durability of Geosynthetic Clay Liners," *Proceedings of the GRI-14 Conference on 'Hot Topics in Geosynthetics– I,'* R.M. Koerner, Y.G. Hsuan, and M.V. Ashley (Eds.), GII Publications, Folsom, P.A. , pp. 116-135.

Daniel, D.E., Correspondence to J. Olsta, 19 March 2001 and 22 November 2000.

HYDRATION OF GCLs ADJACENT TO SOIL LAYERS

An extensive laboratory testing program was undertaken to investigate the potential for hydration of a GCL when placed against a compacted soil layer. Three different GCLs were used to evaluate the effects of hydration time, initial GCL water content, thickness of soil layer and overburden pressure.

Tests were conducted using a low plasticity clay, commonly found in the Cincinnati, Ohio area. Specimens of GCL with a known moisture content, were placed in a specially designed test apparatus, where a soil with a known moisture content was compacted into the base and the GCL was placed on top. The specimen was then loaded with a load platen and allowed to hydrate for a specific amount of time. At the end of the hydration period, the GCL was tested for moisture content. The GCL was left in contact with the soil for periods of 5, 25 and 75 days to define the effect of test duration on the hydration of the GCL.

Test results show that significant increases in the moisture content of a GCL may occur in the first few days of a GCL's contact with a soil stratum. Overburden pressures within the range tested (i.e. 5 to 390 kPa) did not deter the hydration process, but a larger soil thickness resulted in a larger increase in GCL moisture content.

TR-222
Revised 1/01

United States
Environmental Protection
Agency

Office of Research and
Development
Washington DC 20460

EPA/600/R-96/149
June 1996

EPA

Report of 1995 Workshop on Geosynthetic Clay Liners

HYDRATION OF GCLs ADJACENT TO SOIL LAYERS

Overview of Testing Program

The authors conducted an extensive laboratory testing program to evaluate the potential for hydration of GCLs placed against a compacted subgrade soil layer. Hydration tests were performed on three different GCL products to evaluate the effects of: (i) test duration (i.e., hydration time); (ii) soil initial water content; (iii) thickness of soil layer; and (iv) overburden pressure. Three commercially-available GCL products, namely, Claymax®, Bentomat®, and Bentofix® were used in the testing program. The soil used in the testing program was obtained from the USEPA GCL Field Test Site at the ELDA-RDF facility in Cincinnati, Ohio. This material is classified as low plasticity clay (CL) based on the Unified Soil Classification System (USCS). Tests were performed on two different soil samples and consistent results were obtained between samples. The results reported herein were obtained from tests on a sample with 99 percent of the soil passing the U.S. No. 200 standard sieve and 33 percent smaller than 2 μm (clay fraction). The liquid limit of the soil is 41 and the plasticity index is 19. The soil has an optimum moisture content (OMC) of 20 percent and a maximum dry unit weight of 16.7 kN/m^3 based on the standard Proctor compaction method (ASTM D 698).

Testing Apparatus and Procedure

Figure 11 shows the apparatus specially designed to conduct the GCL hydration tests. The apparatus consists of a polypropylene mold 75 mm in diameter and 150 mm in height. A geomembrane/GCL/soil composite specimen is placed in the mold and covered with two layers of a thin vapor barrier. A loading platen is placed on the specimen for application of overburden pressure.

To process the soil, it was first passed through a U.S. No. 4 standard sieve. The soil was then moisture conditioned to achieve the desired moisture content. The moist soil was placed in the mold in a loose condition and statically compressed to 50-mm thick lifts. The soil was compacted to a dry unit weight equal to approximately 90 percent of the maximum dry unit weight based on the standard Proctor method (ASTM D 698). Two soil lifts were used giving a total thickness of 100 mm. The GCL and geomembrane specimens were carefully trimmed from the same sheets. The initial moisture content of the GCL was measured by taking a small sample from the same GCL sheet and measuring its weight before and after oven drying. The initial moisture content of the GCLs varied between 15 and 20 percent.

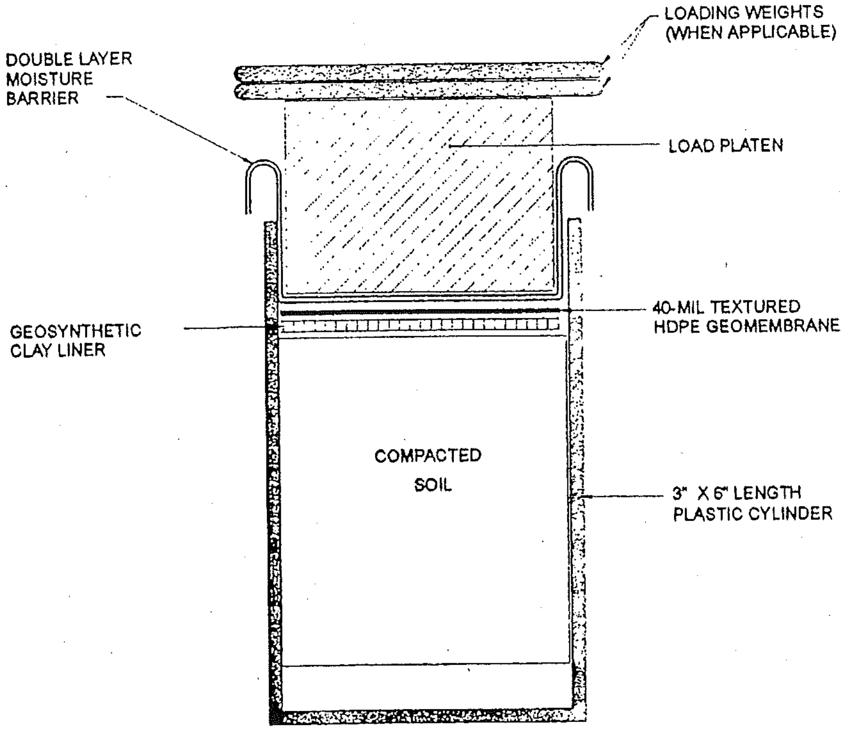


Figure 11. Simplified diagram of GCL hydration test set-up.

The GCL and geomembrane were placed on the soil and covered with the vapor barrier. The side of the GCL placed against the soil was woven in the case of Claymax® and nonwoven for Bentomat® and Bentofix®. Overburden pressure of 10 kPa was applied on the composite specimen utilizing standard weights which were placed on the loading platen. The entire apparatus was then placed in a temperature and humidity controlled room for the desired hydration time period. At the end of the hydration period, the test specimen was removed and the water content of the GCL and soil were measured. The final moisture content of the GCL was measured by weighing the entire GCL specimen before and after oven drying. The final moisture content of the soil was measured as the average water content of three samples obtained from the top, middle, and bottom of the soil specimen.

Testing Conditions and Results

As previously described, test conditions were varied to evaluate the effects of several factors on the hydration of GCLs. To evaluate the effect of test duration, tests were performed where the GCL was in contact with the soil for 5, 25, and 75 days. Soil specimens were compacted to initial moisture contents equal to OMC, 4 percentage points dry of OMC, and 4 percentage points wet of OMC to evaluate the effect of soil initial moisture content on GCL hydration.

Figures 12, 13, and 14 present the results of the hydration tests for the GCL products Claymax®, Bentomat®, and Bentofix®, respectively. These figures show that the moisture content of all three GCLs increased significantly as a result of contact with compacted subgrade soil. The increase in GCL water content was significant after only five days of hydration. With increasing time, GCL water content continued to increase at a decreasing rate. For most tests, GCL water content reached a maximum value after about 25 days of soil contact and for some of the tests water content continued to increase even after 75 days of hydration. It is interesting to note that all three GCL products showed relatively similar behavior. Increases in water content were comparable for the three GCL products despite differences in GCL fabric (i.e., woven vs. nonwoven) and types of bentonite clay used to manufacture the GCLs.

Figures 12, 13, and 14 illustrate the influence of soil subgrade initial moisture content on the hydration of GCLs. From these figures, it is evident that the moisture content of the GCL for any particular hydration time increases as the initial moisture content of the soil increases. These figures also show that a small increase in soil initial moisture content can have a significant impact on GCL moisture content. For example, after 75 days of hydration, the moisture content of Claymax® was approximately 16 percent higher when the initial moisture content of the soil was equal to OMC than when it was 4 percentage points drier than OMC. This behavior is expected because more water is available in the soil for the GCL to hydrate.

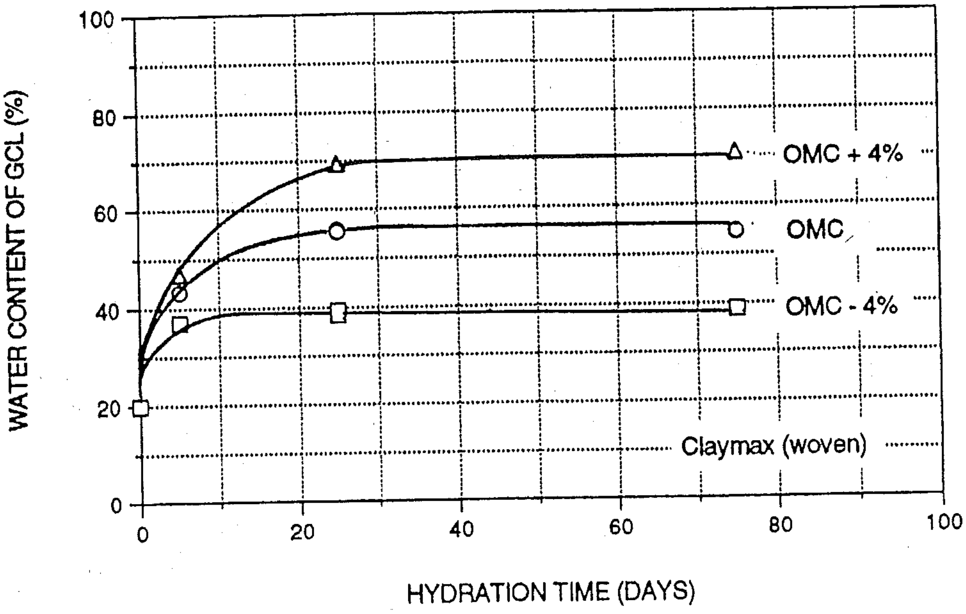


Figure 12. Increase in GCL moisture content due to contact with compacted subgrade soil: Claymax® with woven geotextile against soil.

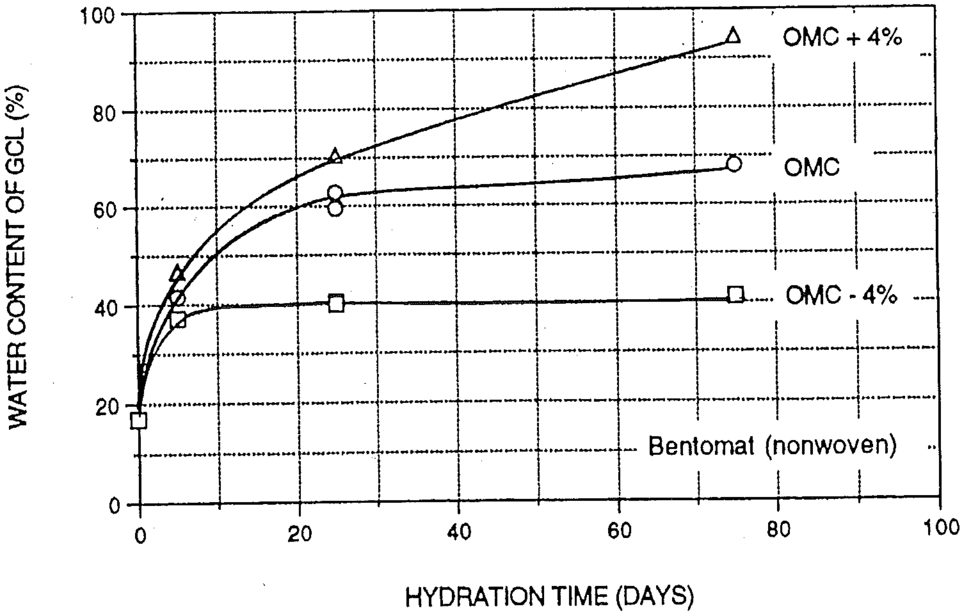


Figure 13. Increase in GCL moisture content due to contact with compacted subgrade soil: Bentomat® with nonwoven geotextile against soil.

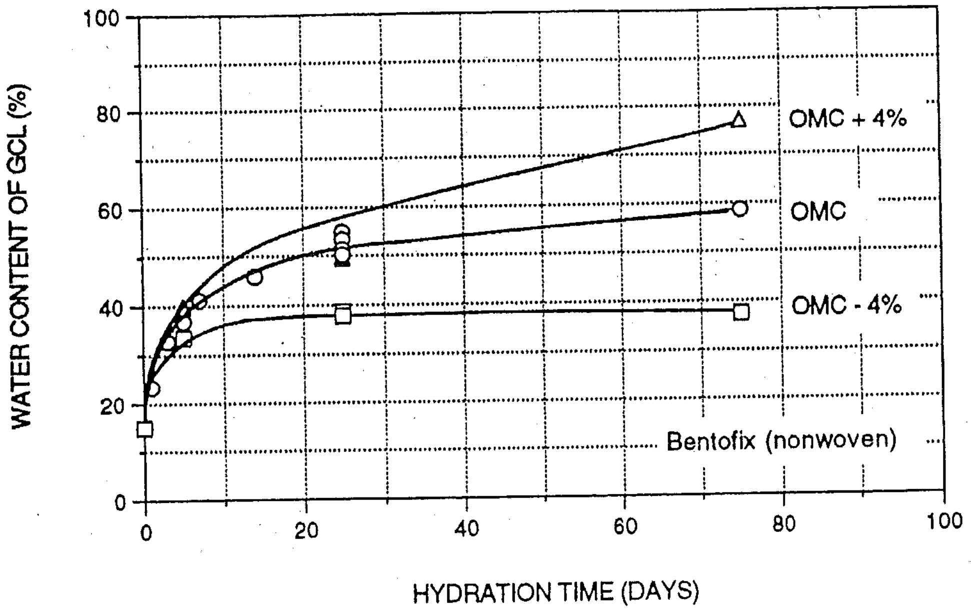


Figure 14. Increase in GCL moisture content due to contact with compacted subgrade soil: Bentofix® with nonwoven geotextile against soil.

The examination of the curves shown in Figures 12, 13, and 14 shows that the time required for the GCL to reach its final moisture content is less in the case of a dry soil than in the case of a wet soil. At the lowest soil initial moisture content tested, GCL moisture content ceased to increase after about 5 to 25 days. At the highest initial moisture content tested, the Bentomat® and Bentofix® GCLs continued to increase in moisture content after 75 days of hydration.

To evaluate the effect of soil layer thickness, specimens were prepared using 50, 100, 150, and 200 mm of soil thickness. Soil initial moisture content was 20 percent and dry unit weight was 14.9 kN/m^3 for all specimens. Figure 15 shows the results of hydration tests for the Bentofix® GCL after 25 days of hydration. The GCL moisture content increased with the increase of the soil layer thickness. However, it appears that only a small change in moisture content increase occurs for thicknesses greater than 100 mm.

The effect of overburden pressure on GCL hydration is illustrated in Figure 16 for the Bentofix® GCL. As shown in this figure, overburden pressure in the range of 5 to 390 kPa did not significantly affect the rate of GCL hydration during the 25-day test duration.

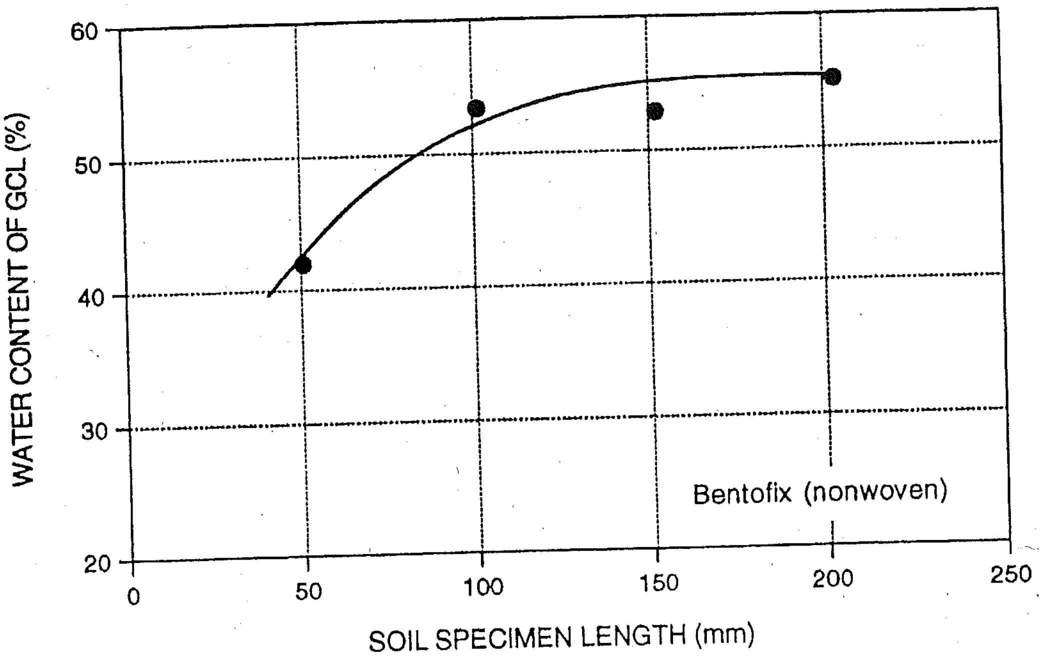


Figure 15. Influence of subgrade soil layer thickness on GCL moisture content.

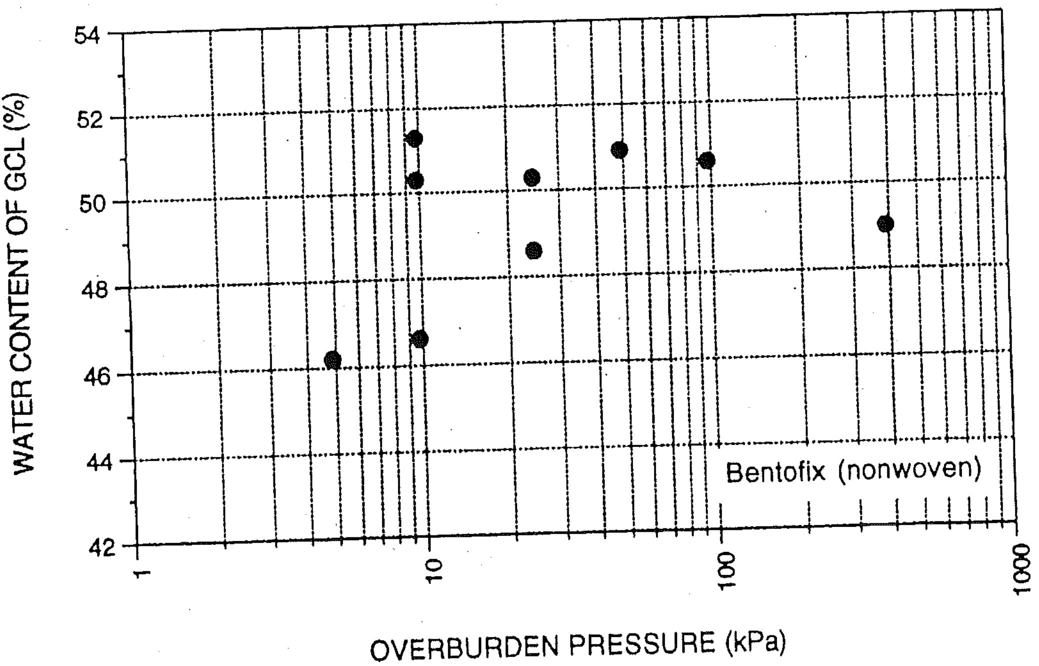


Figure 16. Influence of overburden pressure on the increase in GCL moisture content.

Summary

From the testing program results described above, the following can be concluded:

- GCLs will hydrate when placed in contact with subgrade soils compacted within the range of moisture contents typically found in earthwork construction specifications; this conclusion is consistent with data provided by Daniel et al. [1993]; even for the driest soil (compacted 4 percentage points dry of OMC), GCL moisture contents consistently increased from an initial value in the range of 15 to 20 percent up to about 40 percent within a 100-day period; it should thus be anticipated that GCLs placed even against relatively dry compacted subgrades will undergo substantial hydration;

- given that Daniel et al. [1993] have shown that long-term GCL shear strengths are insensitive to water content for water contents above about 50 percent, stability analyses involving GCLs placed in contact with compacted subgrade soils should be based on hydrated GCL shear strengths;

- significant increases in GCL moisture contents may occur within a few days of GCL contact with a moist soil; the rate of GCL hydration is initially highest and then decreases with increasing time;

- within the range of conditions tested a higher soil moisture content results in a higher GCL moisture content;

- larger soil layer thickness results in a larger increase in GCL moisture content, however, for soil layer thicknesses greater than 100 mm only insignificant increases were observed with increasing soil layer thickness;

- overburden pressure within the range tested (i.e., 5 to 390 kPa) did not influence the hydration process; and

- differences between GCL products tested (i.e., type of bentonite clay and fabric) did not seem to significantly affect the test results.

MOISTURE RETENTION CHARACTERISTICS OF CLAYMAX® IN HOT, ARID CONDITIONS

Claymax was exposed to long-term arid conditions to determine its moisture retention characteristics. Three specimens of Claymax were tested with different overburden pressures to simulate different field soil cover conditions. All specimens were hydrated in fresh water approximately 24 hours before testing began. Following hydration, test specimens were placed in an environmental chamber to simulate daytime and nighttime conditions in an arid environment. Water content measurements were performed on the Claymax specimens throughout the test duration in the arid environment.

Test number 1 was performed without any confining pressure. Test number 2 was performed with a confining pressure equivalent to 70 psf and test specimen number 3 was performed with a confining pressure equivalent to 160 psf. Water content samples were periodically taken from the Claymax and from the overlying sand used to provide the confining pressure.

Test results indicate that the application of an overburden soil to Claymax enhances its moisture retention characteristics. The water content of Claymax with sand cover does not decrease significantly when subjected to arid conditions lasting up to several months.

TR-106
Revised 12/00

FINAL REPORT
OF
CLAYMAX MOISTURE RETENTION
TEST PROGRAM

Prepared for

James Clem Corporation
444 North Michigan, Suite 1610
Chicago, Illinois 60611

Prepared by

GeoServices Inc. Consulting Engineers
Geomechanics and Environmental Laboratory
1600 Oak Brook Drive, Suite 565
Norcross, Georgia 30093

GeoServices Project Number: P1138
2 February 1990

1. INTRODUCTION

1.1 Terms of Reference

This report was prepared by Mr. John R. Bennett and Mr. Scott M. Luettich, P.E. and was reviewed by Dr. Neil D. Williams, P.E. of GeoServices, Inc. Consulting Engineers (GeoServices). The work was conducted at GeoServices Geomechanics and Environmental Laboratory (GEL) in Norcross, Georgia at the request of Mr. William J. Simpson of James Clem Corporation (Clem).

GeoServices was requested to perform laboratory tests to evaluate the moisture retention properties of CLAYMAX liner under simulated dry, arid conditions. The work is being performed in general accordance with GEL Proposal Number XG89511, issued to James Clem Corporation on 14 February 1989, the Proposal Addendum issued on 14 August 1989, and the letter of authorization issued by Clem on 12 December 1989.

1.2 Report Organization

This report is organized as follows:

* Section 1 presents the terms of reference and report organization;

* Section 2 presents the purpose and scope of the work;

* Section 3 presents details of the test equipment and procedure; and

* Section 4 presents the results of the tests.

2. PURPOSE AND SCOPE OF WORK

The purpose of the test program was to measure the moisture retention characteristics of CLAYMAX when exposed to long term arid environments. The scope of the work included monitoring the moisture content of three hydrated samples of CLAYMAX placed in a temperature and humidity-controlled chamber. Different overburden pressures were applied to each of the three samples to simulate various soil cover conditions. Water content measurements were obtained from the CLAYMAX samples regularly throughout the ten-month test duration.

3. TEST EQUIPMENT AND PROCEDURES

3.1 Test Equipment

All tests were performed in a climate-controlled chamber, approximately 5 ft (1.5 m) long by 3 ft (0.9 m) wide by 2 ft (0.6 m) deep. The chamber operates on a timed cycle in order to simulate day and night conditions. The chamber maintains a constant temperature of 95±2°F with a relative humidity of 30±5% during the day cycle, and a temperature of 70±2°F with a relative humidity of 50±5% during the night cycle.

3.2 Test Procedures

3.2.1 Test Number 1

Test Number 1 was performed using a specimen of CLAYMAX approximately 12 in. (30 cm) by 7 in. (18 cm). The specimen was hydrated with water for 24 hours in a pan approximately 3 in. (8 cm) deep without any confining stress (overburden soil) applied to the specimen. After hydration, the specimen was placed in the climate-controlled chamber and the exposure was started on 18 February 1989. Water content samples were taken regularly from the bentonite specimen and the moisture content was determined in accordance with ASTM D-2216.

3.2.2 Test Number 2

Test Number 2 was performed using a specimen of CLAYMAX approximately 12 in. (30 cm) by 7 in. (18 cm). The specimen was hydrated for 24 hours, in a deep pan with 8 in. (20 cm) of overburden soil (ASTM C-33 concrete sand) placed over the specimen. This resulted in an overburden pressure of approximately 70 psf (3.5 kPa). After hydration, the specimen was placed in the climate-controlled chamber and the exposure period was started on 18 February 1989. Water content samples were taken regularly from the CLAYMAX specimen and from the overlying sand at depths of 0,1.5, and 8 in. (0,4,and 20 cm).

3.2.3 Test Number 3

Test Number 3 was performed using a specimen of CLAYMAX approximately 18 in. (45 cm) by 30 in. (76 cm). The specimen was hydrated for 24 hours in a box approximately 19 in. (49 cm) deep with 18 in. (46 cm) of overburden soil (sand) applied to the specimen. This resulted in an overburden pressure of approximately 160 psf (8 kPa). After hydration, the specimen was placed in the climate-controlled chamber and the exposure period was started on 18 February 1989. Water content samples were taken regularly from the CLAYMAX and from the overlying sand at depths of 0,8, and 18 in. (0,20,and 46 cm). After a total drying period of ten months, Sample 3 was excavated and photographs were obtained. These photographs (enclosed with this report) indicate fairly widespread dessication, with the average width of the dessication cracks measured to be approximately 0.25 in. (0.64 cm).

4. TEST RESULTS

4.1 Test Number 1

Hydration of the CLAYMAX specimen under zero confining stress resulted in a significant increase in thickness from approximately 0.2 in. (0.5 cm) to slightly over 1.5 in. (3.8 cm) after the 24-hour hydration period. Initial water content samples of the specimen, obtained immediately after the 24-hour hydration period, indicated an average value of approximately 1300%. Water content samples were again taken after four days of exposure. An average value of approximately 700% was obtained. Water content samples were again taken after 21, 47, and 90 days. The average values obtained were less than 15%, 6%, and 1% respectively. Visual inspections of the specimen during the test revealed dessication, cracking and separation of the bentonite within 5 days of starting the exposure conditions. The water content results are presented in Table 1. The water content values of the bentonite are plotted as a function of time as shown in Figure 1-A, included in the Appendix.

4.2 Test Number 2

Hydration of CLAYMAX under 8 in. (20 cm) of sand resulted in an increase in thickness from approximately 0.2 in. (0.5 cm) to approximately 0.3 in. (0.75 cm) after 24 hours. Initial water content samples indicated an average value of approximately 250% for the CLAYMAX and approximately 11% to 12% for the overlying sand. Water content samples were taken from the sand and CLAYMAX after 3, 15, 25, 40, 90, 154, 235, and 294 days of exposure. These results are presented in Table 2. The water content of the sand, plotted as a function of time, is shown in Figure 2-A. The water content of the bentonite as a function of time is shown in Figure 2-B.

4.3 Test Number 3

Hydration of CLAYMAX under 18 in. (48 cm) of sand resulted in an increase in thickness from approximately 0.2 in. (0.5 cm) to approximately 0.3 in. (0.75 cm). Initial water content samples indicated an average value of 300% for the CLAYMAX specimen and 10% to 11% for the overlying sand. Water content samples were again taken from the sand and CLAYMAX after 3, 15, 25, 40, 90, 154, 235, and 294 days of exposure. These results are presented in Table 3. Water content values are plotted as a function of time for the sand and bentonite, as shown in Figures 3-A and 3-B, respectively.

4.4 Discussion

The water content and thickness of the CLAYMAX specimen hydrated under zero confining stress (Test Number 1) were initially much higher than for the CLAYMAX specimens hydrated under positive confining stresses (Tests Number 2 and 3). The water content of the unconfined CLAYMAX specimen decreased rapidly as the test progressed, whereas the water content of CLAYMAX did not decrease significantly when subjected to confining pressure. The initial hydration characteristics as well as the long-term moisture retention characteristics of CLAYMAX were apparently influenced greatly by the application of confining pressure. Furthermore, the insulation effect (both temperature and humidity) of the overlying sand apparently enhanced the moisture retention characteristics of the CLAYMAX. The test results did not indicate a significant difference in moisture retention between Tests Number 2 and 3.

APPENDIX

Table 1
Water Content Results

Test Number 1

		Elapsed Time (days)				
Soil Type	Depth (in.)	0	4	21	47	90
Bentonite	0	1300%	690%	15%	6%	1%

Table 2
Water Content Results

Test Number 2

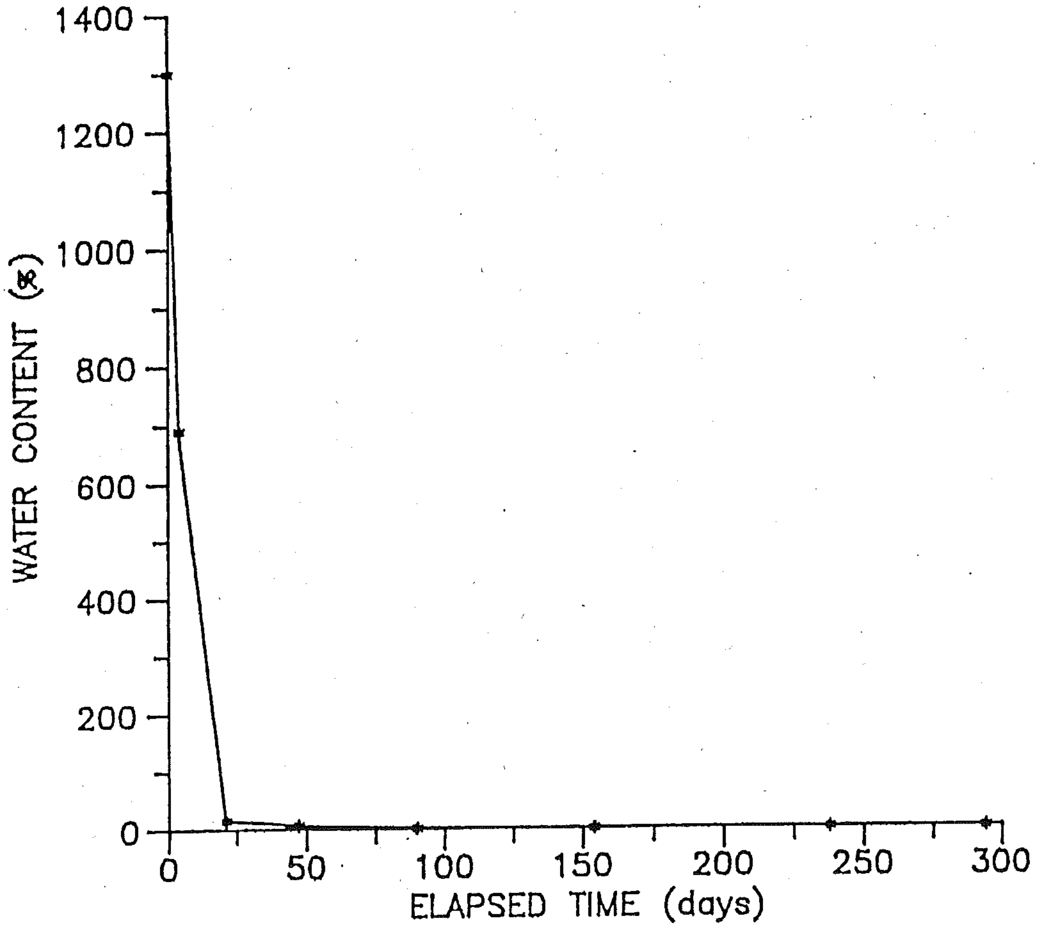
Soil Type	Depth (in.)	Elapsed Time (days)								
		0	3	15	25	40	90	154	235	294
Sand	0	11%	0.8%	0.1%	0	0	0	0	0	0
Sand	1.5	11%	7%	7%	7%	5%	0.2%	0	0	0
Sand	8.0	12%	8%	7%	7%	7%	1%	0	0	0
Bentonite	8.5	260%	--	--	280%	--	260%	180%	20%	1%

Table 3
Water Content Results

Test Number 3

		Elapsed Time (days)								
Soil Type	Depth (in.)	0	3	15	25	40	90	154	235	294
Sand	0	6%	0.3%	0.1%	0	0	0	0	0	0
Sand	8	12%	8%	8%	8%	8%	3%	0.4%	0	0
Sand	18	18%	16%	13%	12%	11%	5%	3.5%	2%	0
Bentonite	18.5	300%	--	--	265%	--	248%	203%	116%	37%

MOISTURE RETENTION
CLAYMAX
TEST No. 1



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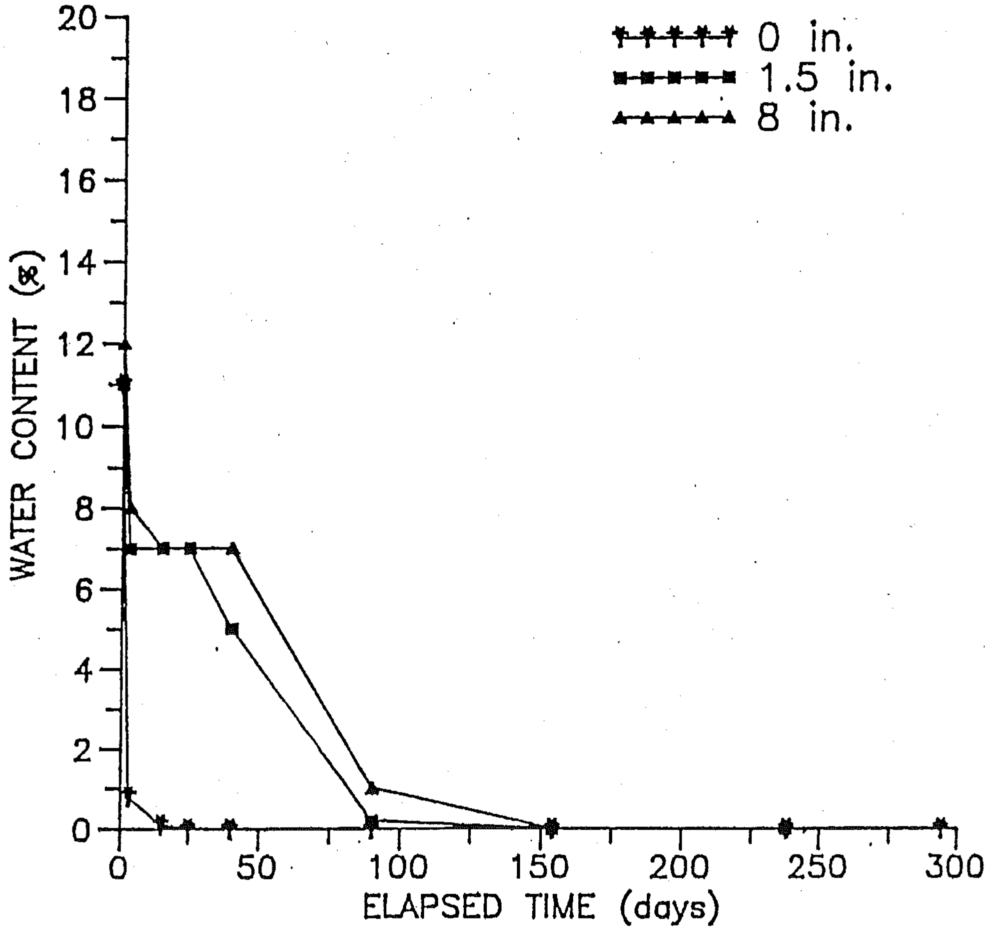
GEOTECHNICAL LABORATORY

FIGURE NO.	1-A
PROJECT NO.	P1138
DOCUMENT NO.	NL90020
PAGE NO.	

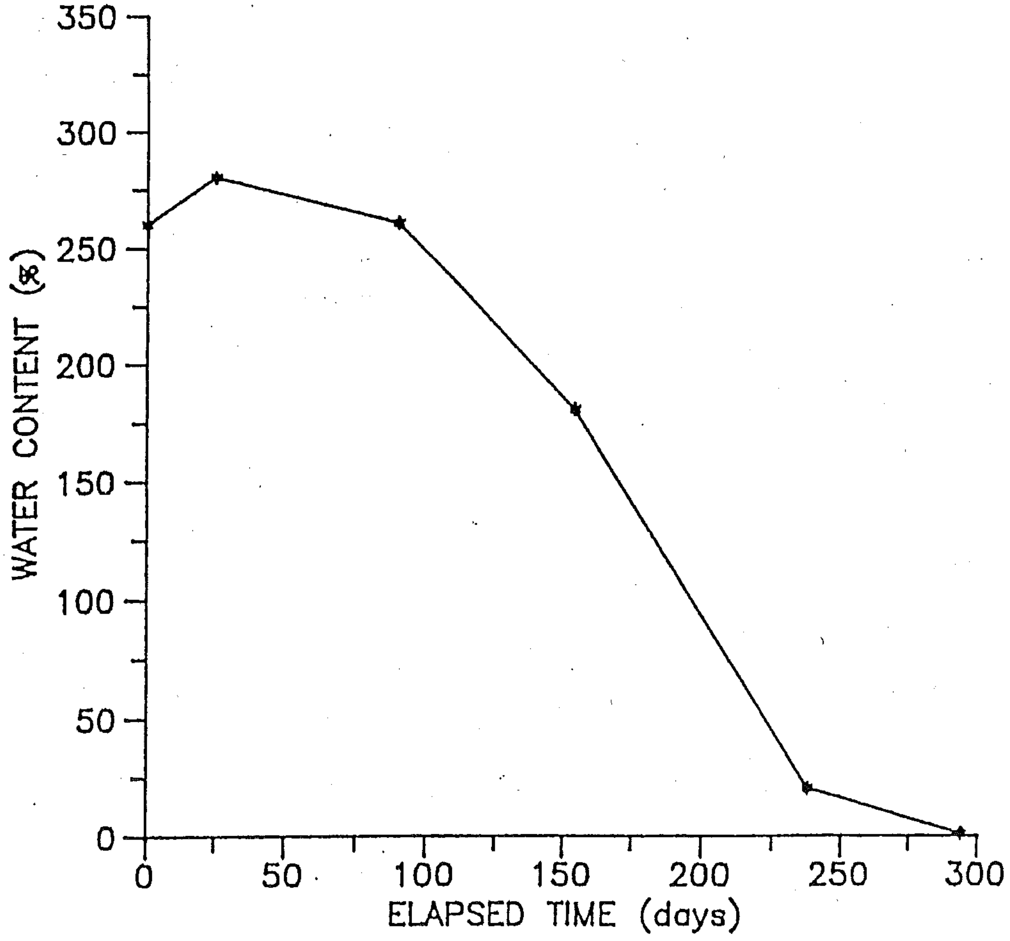
MOISTURE RETENTION
SAND OVERBURDEN
TEST No. 2



GeoServices Inc. CONSULTING ENGINEERS GEOTECHNICAL LABORATORY	FIGURE NO. 2-A PROJECT NO. P1138 DOCUMENT NO. NL90020 PAGE NO.

MOISTURE RETENTION
CLAYMAX
TEST No. 2

CONFINING STRESS = 70 psf (3.5 kPa)



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GEOTECHNICAL LABORATORY

FIGURE NO.	2-B
PROJECT NO.	P1138
DOCUMENT NO.	NL90020
PAGE NO.	

MOISTURE RETENTION
SAND OVERBURDEN
TEST No. 3

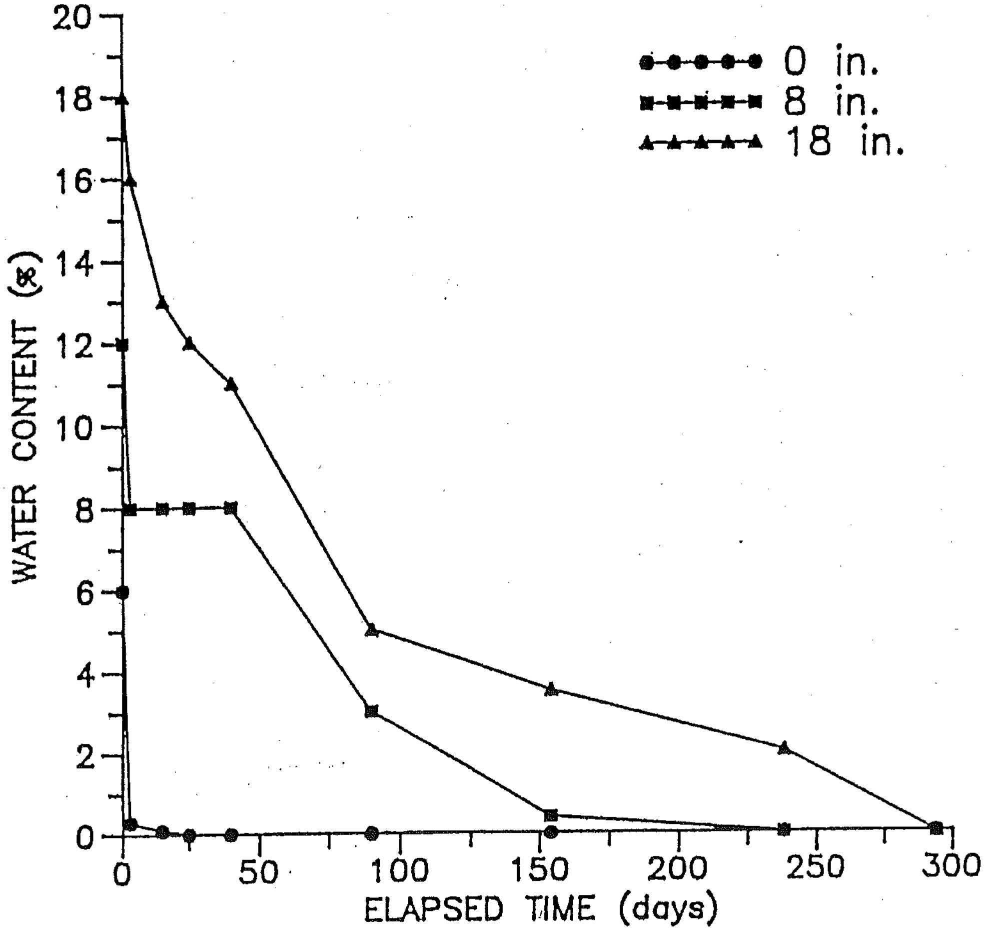

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FIGURE NO. 3-A
PROJECT NO. P1138
DOCUMENT NO. NL90020
PAGE NO.

MOISTURE RETENTION
CLAYMAX
TEST No. 3

CONFINING STRESS = 160 psf (8kPa)

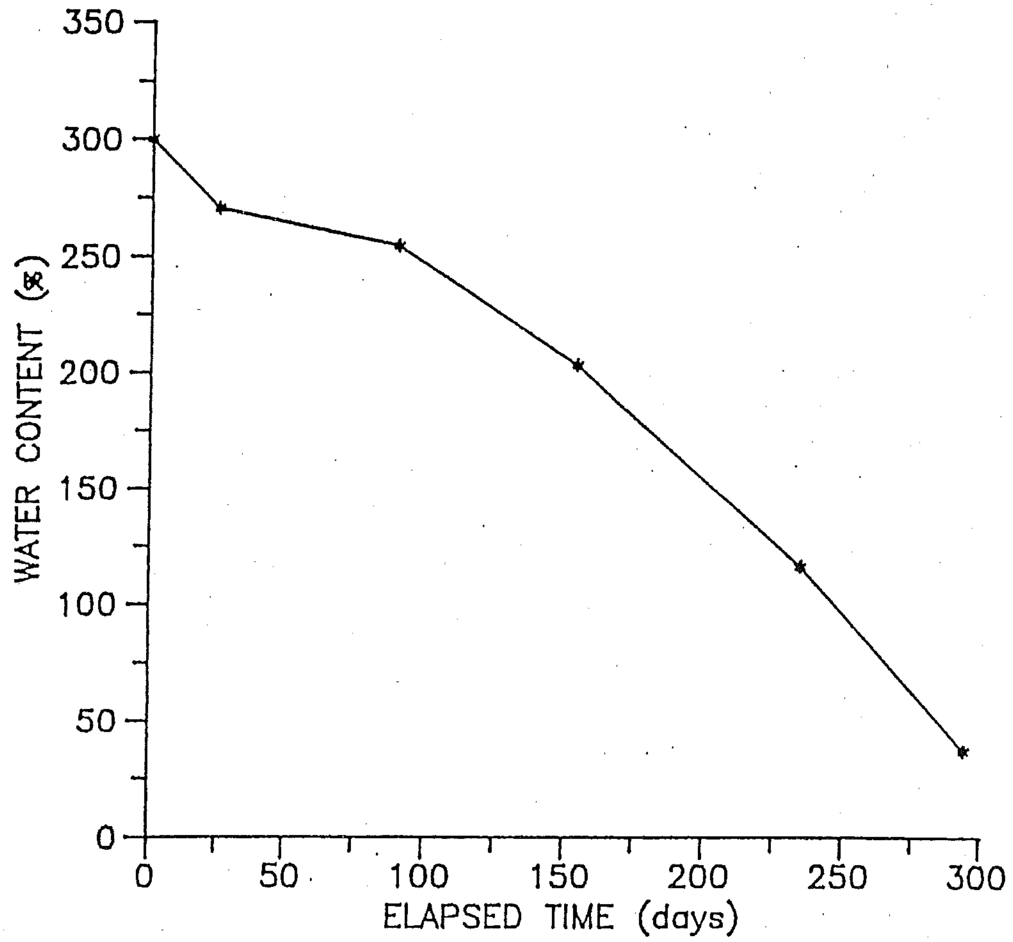

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FIGURE NO.	3-B
PROJECT NO.	P1138
DOCUMENT NO.	NL90020
PAGE NO.	

geosynthetic clay liners • geosynthetic clay liners • geosynthetic clay liners

CETCO
LINING TECHNOLOGIES

GCL Performance & Design Reference

GCL USE IN ALTERNATIVE LINER SYSTEMS OF DOUBLE-LINED LANDFILLS

Since their inception in the 1980s, GCLs have been used in the upper composite of double liner systems with leak detection in a number of landfills. Twelve states require double liner systems for municipal solid waste landfills (MSWLFs) (Koerner, et. al., 1998). The GCL component of the composite liner is often considered to be an alternate to the regulated low permeability compacted soil (or compacted clay liner, i.e., CCL) per 40 CFR 25.8.28(a)(2). This regulation calls for the CCL to be at least 2-ft thick with a permeability of 1 × 10^{-7} cm/sec, or less. The alternate, in this case GCL, must be equivalent, or superior, in its performance to the CCL.

The underlying leak detection system allows for an assessment of the upper liner's performance. A major study has just been completed for the USEPA, which includes 91 landfills containing 287 single or multiple cells (Bonaparte, et. al., 1999). Three different types of primary liners were involved (GM alone, GM/CCL and GM/GCL) and two types of leak detection materials (sand and geonet). Thus six combinations are available, as shown in Table 1. Data is also available for three different stages during the life of the respective landfill cells (initial, active and post closure).

Table 1 – Leakage Rates from Leak Detection Systems of Double-Lined Landfills (Bonaparte, et. al., 1999)

[All Flow Rates are in Gal/Acre-day (gpad)]

Liner/LDS Type	Type I (GM-Sand)			Type II (GM-GN)			Type III (GM/CCL-Sand)		
Life of Cycle Stage	1	2	3	1	2	3	1	2	3
Average Flow	41	18	6.8	10	11	ND	23	15	6.8
Minimum Flow	0.81	0.0	0.02	0.51	0.15	ND	0.13	2.4	0.0
Maximum Flow	229	158	26	40	38	ND	126	71	29
No. of "points"	30	32	8	7	11	ND	31	41	15
No. of landfills	11	11	4	4	6	ND	11	11	4

Life Cycle Stage: "points" = Number of measuring points (i.e., outlets of single or multiple cells)
Stage 1 – Initial Life
Stage 2 – Active Life
Stage 3 – Post Closure ND = No Detection (of leakage)

Table 1, Continued – Leakage Rates from Leak Detection Systems of Double-Lined Landfills (Bonaparte, et. al., 1999)

[All Flow Rates are in Gal/Acre-day (gpad)]

Liner/LDS Type	Type IV (GM/CCL-GN)			**Type V (GM/GCL-Sand)**			**Type VI (GM/GCL-GN)**		
Life of Cycle Stage	1	2	3	**1**	**2**	**3**	**1**	**2**	**3**
Average Flow	18	8.9	7.0	**14**	**2.38**	**0.03**	**0.70**	**0.28**	**ND**
Minimum Flow	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**ND**
Maximum Flow	74	54	14	**104**	**30**	**0.10**	**3.6**	**1.0**	**ND**
No. of "points"	21	27	12	**19**	**19**	**4**	**6**	**4**	**ND**
No. of landfills	6	9	3	**3**	**3**	**1**	**2**	**2**	**ND**

Life Cycle Stage: "points" = Number of measuring points (i.e., outlets of single or multiple cells)
Stage 1 – Initial Life
Stage 2 – Active Life
Stage 3 – Post Closure ND = No Detection (of leakage)

The above data is plotted in Figure 1 (for the average flow rates) so as to give a graphic representation as to the effectiveness of the GM/GCL alternate barrier system. Note that the plotted data represents the average flow rates of 287 single or multiple cells monitored for up to 10 years. Readily seen is that the alternate GM/GCL outperforms the standard GM/CCL in all cases and at every life cycle stage. Clearly, the GCLs have a significant influence in reducing leakage through the covering geomembranes.

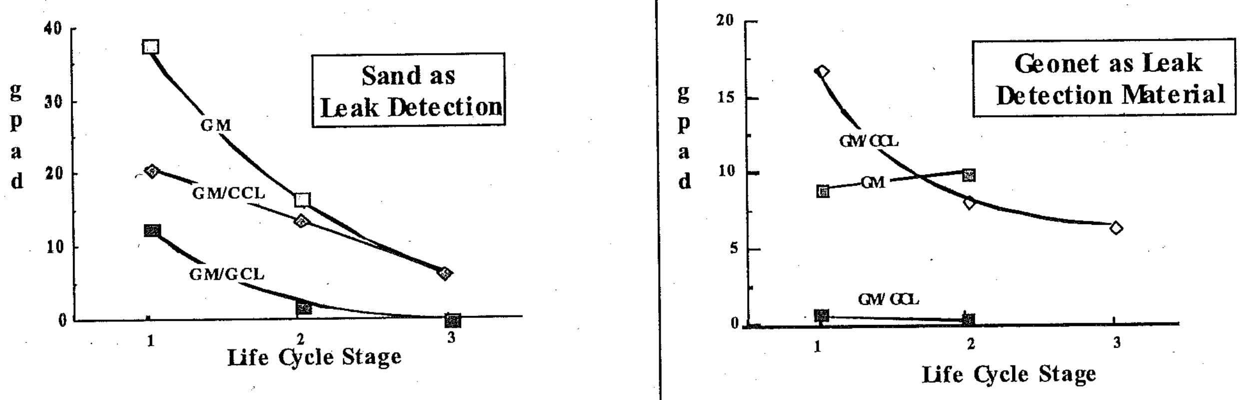


Figure 1 – Leakage Rates for 287 Landfill Cells (Bonaparte, et. al.,)

CONCLUSION

In 1991, when the original EPA regulation on MSWLF liners [40 CFR 258.28 (a)(2)] was promulgated, GCLs were in their infancy. Today, GCLs have been shown to be superior to CCLs in composite liner systems of every common configuration. Based on the results of the Bonaparte study, it can be concluded that a GM/GCL composite liner system defines the current state of the art for minimizing landfill liner leakage.

REFERENCES

Bonaparte, R., Daniel, D. E. and Koerner, R. M., Assessment and Recommendations for Optimal Performance of Waste Containment Systems, EPA/600/R-02/099, December 2002, U. S. EPA, ORD, Cincinnati, OH, www.epa.gov/ORD/NRMRL/Pubs/600R02099/600R02099.pdf.

INDEX FLUX AND PERMEABILITY OF GCL's
TEST RESULTS
ASTM D-5887 / D-5084

JLT

Client : CETCO
Project Location : Xcel Energy
Sample Number : Roll 5773 Lot: 200324FA
Description : Bentomat ST

Permeant Fluid : Distilled Water/LF Leachate

Date : 07-29-03
Job No. : 03LG233.01
Tested By : DB
Checked By : JB

Page : 1 of 2

Physical Property Data

		Total Sample			Total Sample
Initial Clay Height (in)	:	0.20	Final Height of Clay (in)	:	0.33
Initial Diameter (in)	:	4.00	Final Diameter of Clay (in)	:	4.00
Initial Wet Weight (g)	:	48.80	Final Wet Weight(Clay) (g)	:	92.60
Wet Density (pcf)	:	73.90	Wet Density (pcf)	:	84.99
Moisture Content %	:	22.70	Moisture Content %	:	204.28
Dry Density (pcf)	:	60.23	Dry Density (pcf)	:	27.93

Test Parameters

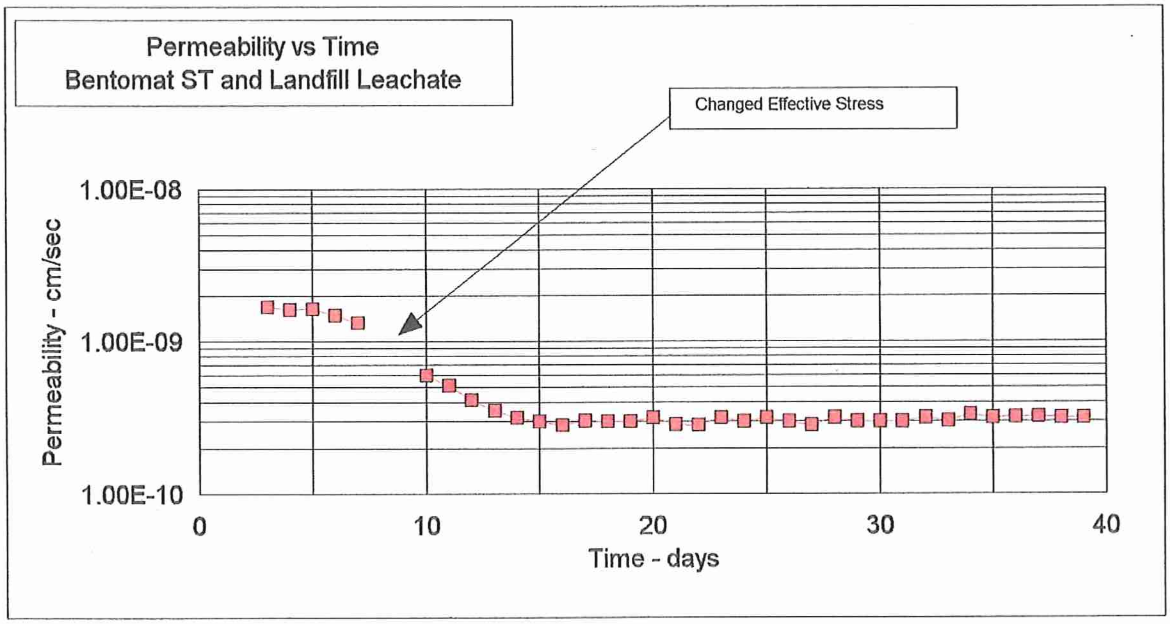
Fluid : Distilled Water/LF Leachate
Cell Pressure (psi) : 26.00 "as- specified"
Head Water (psi) : 17.00 "as- specified"
Tail Water (psi) : 15.00 "as- specified"

Effective
Confining Pressure (psi) : **10**
Gradient : 167.27

Flux and Permeability Input Data

Minimum Saturation Time is 120 hours

Area, A = 0.00811 m^2
Thickness, t = 0.33 in



JLT Laboratories, Inc. *938 S Central Ave, Canonsburg, Pa. 15317 Tel 724-746-4441 , Fax 724-745-4261*

Client : CETCO
Project Location : Xcel Energy
Sample Number : Roll 5773 Lot: 200324FA
Description : Bentomat ST

Permeant Fluid : Distilled Water/LF Leachate

Date : 07-29-03
Job No. : 03LG233.01
Tested By : DB
Checked By : JB

Page : 2 of 2

DAILY FLOW AND PERMEABILITY CALCULATIONS

Days	Date	InFlow	Time	Elapsed	Flux	k
		cc	min	Time (sec)	(m^3/m^2)/sec	cm/sec
1	06/14/2003	120 hours of hydration time				
2	06/20/2003					
3	06/21/2003	5.20	1490	89400	7.2E-09	1.68E-09
4	06/22/2003	6.20	1832	109920	7.0E-09	1.63E-09
5	06/23/2003	4.70	1377	82620	7.0E-09	1.65E-09
6	06/24/2003	4.10	1328	79680	6.3E-09	1.49E-09
7	06/25/2003	3.70	1339	80340	5.7E-09	1.33E-09
8	06/26/2003	Increased Effective Stress to 10 psi				
9	06/27/2003					
10	06/28/2003	1.80	1440	86400	2.6E-09	6.03E-10
11	06/29/2003	3.50	3258	195480	2.2E-09	5.18E-10
12	06/30/2003	0.80	933	55980	1.8E-09	4.14E-10
13	07/01/2003	0.90	1231	73860	1.5E-09	3.53E-10
14	07/02/2003	1.00	1526	91560	1.3E-09	3.16E-10
15	07/03/2003	0.90	1449	86940	1.3E-09	3.00E-10
16	07/04/2003	0.85	1442	86520	1.2E-09	2.84E-10
17	07/05/2003	0.90	1440	86400	1.3E-09	3.02E-10
18	07/06/2003	0.90	1443	86580	1.3E-09	3.01E-10
19	07/07/2003	0.90	1442	86520	1.3E-09	3.01E-10
20	07/08/2003	0.95	1441	86460	1.4E-09	3.18E-10
21	07/09/2003	0.85	1439	86340	1.2E-09	2.85E-10
22	07/10/2003	0.85	1448	86880	1.2E-09	2.83E-10
23	07/11/2003	0.95	1445	86700	1.4E-09	3.17E-10
24	07/12/2003	0.90	1442	86520	1.3E-09	3.01E-10
25	07/13/2003	0.95	1440	86400	1.4E-09	3.18E-10
26	07/14/2003	0.90	1446	86760	1.3E-09	3.00E-10
27	07/15/2003	0.85	1443	86580	1.2E-09	2.84E-10
28	07/16/2003	0.95	1442	86520	1.4E-09	3.18E-10
29	07/17/2003	0.90	1442	86520	1.3E-09	3.01E-10
30	07/18/2003	0.90	1443	86580	1.3E-09	3.01E-10
31	07/19/2003	0.90	1443	86580	1.3E-09	3.01E-10
32	07/20/2003	0.95	1440	86400	1.4E-09	3.18E-10
33	07/21/2003	0.90	1439	86340	1.3E-09	3.02E-10
34	07/22/2003	1.00	1444	86640	1.4E-09	3.34E-10
35	07/23/2003	0.95	1446	86760	1.4E-09	3.17E-10
36	07/24/2003	0.95	1427	85620	1.4E-09	3.21E-10
37	07/25/2003	1.00	1485	89100	1.4E-09	3.25E-10
38	07/26/2003	0.95	1449	86940	1.3E-09	3.16E-10
39	07/27/2003	0.95	1440	86400	1.4E-09	3.18E-10

INDEX FLUX AND PERMEABILITY OF GCL's
TEST RESULTS
ASTM D-5887 / D-5084

Client	:	CETCO	Date	:	07-29-03
Project Location	:	Xcel Energy	Job No.	:	03LG233.01
Sample Number	:	Roll 5773 Lot: 200324FA	Tested By	:	DB
Description	:	Bentomat ST	Checked By	:	JB

Page : 1 of 2

Permeant Fluid : Distilled Water/Pond 2

Physical Property Data

		Total Sample			Total Sample
Initial Clay Height (in)	:	0.20	Final Height of Clay (in)	:	0.25
Initial Diameter (in)	:	4.00	Final Diameter of Clay (in)	:	4.00
Initial Wet Weight (g)	:	50.30	Final Wet Weight(Clay) (g)	:	76.40
Wet Density (pcf)	:	76.18	Wet Density (pcf)	:	92.56
Moisture Content %	:	21.20	Moisture Content %	:	116.14
Dry Density (pcf)	:	62.85	Dry Density (pcf)	:	42.83

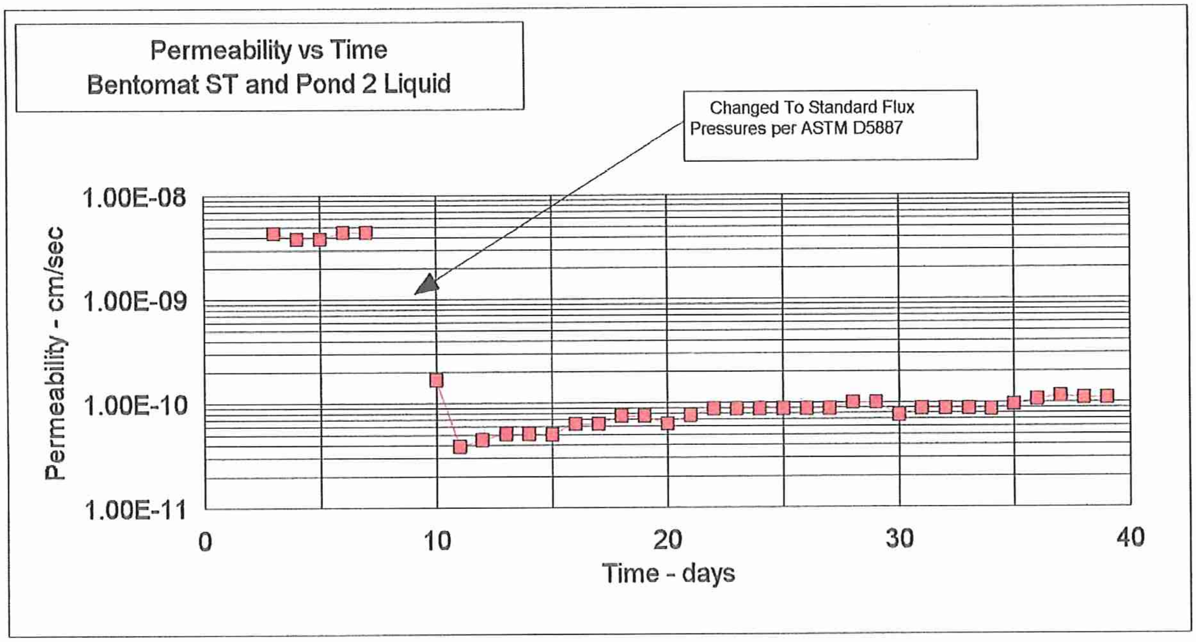
Test Parameters

Fluid	:	Distilled Water/Pond 2			
Cell Pressure (psi)	:	80.00 "as- specified"	**Effective Confining Pressure (psi)**	:	4
Head Water (psi)	:	77.00 "as- specified"	Gradient	:	220.80
Tail Water (psi)	:	75.00 "as- specified"			

Flux and Permeability Input Data

Minimum Saturation Time is 120 hours

Area, A = 0.00811 m^2
Thickness, t = 0.25 in


Permeability vs Time
Bentomat ST and Pond 2 Liquid

Changed To Standard Flux Pressures per ASTM D5887

Client : CETCO
Project Location : Xcel Energy
Sample Number : Roll 5773 Lot: 200324FA
Description : Bentomat ST

Permeant Fluid : Distilled Water/Pond 2 Fluid

Date : 07-29-03
Job No. : 03LG233.01
Tested By : DB
Checked By : JB

Page : 2 of 2

DAILY FLOW AND PERMEABILITY CALCULATIONS

Days	Date	InFlow	Time	Elapsed	Flux	k
		cc	min	Time (sec)	(m^3/m^2)/sec	cm/sec
1	06/14/2003	120 hours of hydration time				
2	06/20/2003					
3	06/21/2003	17.80	1480	88800	2.5E-08	4.40E-09
4	06/22/2003	14.60	1382	82920	2.2E-08	3.86E-09
5	06/23/2003	14.70	1397	83820	2.2E-08	3.85E-09
6	06/24/2003	16.10	1327	79620	2.5E-08	4.43E-09
7	06/25/2003	16.30	1335	80100	2.5E-08	4.46E-09
8	06/26/2003	Changed to Standard Flux Test Pressures per ASTM D-5887				
9	06/27/2003					
10	06/28/2003	1.50	3259	195540	9.5E-10	1.68E-10
11	06/29/2003	0.10	933	55980	2.2E-10	3.92E-11
12	06/30/2003	0.15	1210	72600	2.5E-10	4.53E-11
13	07/01/2003	0.20	1419	85140	2.9E-10	5.15E-11
14	07/02/2003	0.20	1433	85980	2.9E-10	5.10E-11
15	07/03/2003	0.20	1445	86700	2.8E-10	5.06E-11
16	07/04/2003	0.25	1440	86400	3.6E-10	6.35E-11
17	07/05/2003	0.25	1448	86880	3.5E-10	6.31E-11
18	07/06/2003	0.30	1451	87060	4.3E-10	7.56E-11
19	07/07/2003	0.30	1449	86940	4.3E-10	7.57E-11
20	07/08/2003	0.25	1440	86400	3.6E-10	6.35E-11
21	07/09/2003	0.30	1442	86520	4.3E-10	7.60E-11
22	07/10/2003	0.35	1444	86640	5.0E-10	8.86E-11
23	07/11/2003	0.35	1446	86760	5.0E-10	8.85E-11
24	07/12/2003	0.35	1440	86400	5.0E-10	8.88E-11
25	07/13/2003	0.35	1439	86340	5.0E-10	8.89E-11
26	07/14/2003	0.35	1442	86520	5.0E-10	8.87E-11
27	07/15/2003	0.35	1444	86640	5.0E-10	8.86E-11
28	07/16/2003	0.40	1456	87360	5.6E-10	1.00E-10
29	07/17/2003	0.40	1462	87720	5.6E-10	1.00E-10
30	07/18/2003	0.30	1438	86280	4.3E-10	7.62E-11
31	07/19/2003	0.35	1441	86460	5.0E-10	8.88E-11
32	07/20/2003	0.35	1440	86400	5.0E-10	8.88E-11
33	07/21/2003	0.35	1442	86520	5.0E-10	8.87E-11
34	07/22/2003	0.35	1467	88020	4.9E-10	8.72E-11
35	07/23/2003	0.40	1519	91140	5.4E-10	9.62E-11
36	07/24/2003	0.45	1521	91260	6.1E-10	1.08E-10
37	07/25/2003	0.50	1584	95040	6.5E-10	1.15E-10
38	07/26/2003	0.45	1477	88620	6.3E-10	1.11E-10
39	07/27/2003	0.45	1481	88860	6.2E-10	1.11E-10

EFFECT OF WET-DRY CYCLING ON SWELLING AND HYDRAULIC CONDUCTIVITY OF GCLs

By Ling-Chu Lin[1] and Craig H. Benson,[2] Members, ASCE

ABSTRACT: Atterberg limits, free swell, and hydraulic conductivity tests were conducted to assess how wet-dry cycling affects the plasticity and swell of bentonite, and the hydraulic conductivity of geosynthetic clay liners (GCLs) hydrated with deionized (DI) water (pH 6.5), tap water (pH 6.8), and 0.0125-M $CaCl_2$ solution (pH 6.2). The plasticity of bentonite hydrated with DI water increased during each wetting cycle, whereas the plasticity of bentonite hydrated with tap water and $CaCl_2$ decreased during each wetting cycle. Wet-dry cycling in DI water and tap water had little effect on swelling of the bentonite, even after seven wet-dry cycles. However, swelling decreased dramatically after two wetting cycles with $CaCl_2$ solution. Hydraulic conductivity of GCL specimens remained low during the first four wetting cycles ($\sim 1 \times 10^{-9}$ cm/s). However, within five to eight cycles, the hydraulic conductivity of all specimens permeated with the 0.0125-M $CaCl_2$ solution increased dramatically, to as high as 7.6×10^{-6} cm/s. The hydraulic conductivity increased because cracks, formed during desiccation, did not fully heal when the bentonite rehydrated. In contrast, a specimen continuously permeated for 10 months with the 0.0125-M $CaCl_2$ solution had low hydraulic conductivity ($\sim 1 \times 10^{-9}$ cm/s), even after eight pore volumes of flow.

INTRODUCTION

Most cover systems at waste-containment facilities contain a layer having low hydraulic conductivity to impede percolation into the waste. Geosynthetic clay liners (GCLs) are being used with increasing frequency as this low hydraulic conductivity layer. GCLs are factory-manufactured products that consist of a layer of bentonite sandwiched between two geotextiles, or glued to a geomembrane (Estornell and Daniel 1992). GCLs have received widespread use because of their ease of installation, very low hydraulic conductivity, and a perceived resistance to environmental distresses such as frost action and desiccation (Shan and Daniel 1991; Boardman and Daniel 1997; Kraus et al. 1997).

Recent field studies have suggested that GCLs in covers can be damaged by wet-dry cycling in the presence of natural pore waters, which typically are rich in divalent cations such as Ca^{2+} and Mg^{2+} (James et al. 1997; Melchior 1997). James et al. (1997) found fine cracks in GCLs placed in caps over five water-storage reservoirs after excessive leakage from the caps prompted an investigation. The cracks were attributed to a reduction in swelling caused by the exchange of Ca^{2+} in the infiltrating water for Na^{+} in the bentonite. Melchior (1997) also found higher leakage rates than anticipated from a GCL placed in a final cover test section in Hamburg, Germany. Melchior (1997) reports that the swelling capacity of Na-bentonite in the GCL was reduced to values typical of Ca-bentonite after several wet-dry cycles due to the exchange of Ca^{2+} from the pore water in overlying soils for Na^{+}. The reduced swell capacity of the GCL was insufficient to seal preferential flow paths formed during desiccation when the GCLs dehydrated in the summer months, resulting in excessive leakage.

This study was prompted by the field reports of James et al. (1997) and Melchior (1997). The goal was to evaluate how wet-dry cycling with different waters affects the plasticity and swelling of bentonite, and the hydraulic conductivity (K) of GCLs. The waters used included deionized (DI) water, tap water, and 0.0125-M $CaCl_2$. The $CaCl_2$ solution was used to simulate natural pore waters based on an analysis of pore-water extracts from natural vegetated soils in Wisconsin.

BACKGROUND

Properties of Bentonite

The most significant component of the bentonite in GCLs is sodium montmorillonite, a member of the smectite family (Egloffestein 1995). Montmorillonites have a high specific surface area, weak interlayer bonds, and a high cation exchange capacity, which are responsible for their high shrink-swell potential. Water and exchangeable cations can easily enter and separate the layers, causing montmorillonites to swell. In addition, the sodium cations initially existing between the layers in Na-bentonite are easily replaced by multivalent cations (e.g., Ca^{+2}, Mg^{+2}).

Na-bentonites have low hydraulic conductivity because of the thick diffuse double layer and small particle size associated with the montmorillonite fraction, both of which contribute to small and tortuous flow paths (Mesri and Olson 1971). The thick DDL associated with Na-bentonite is reflected by its large swell capacity. Na-bentonites can swell to 8–10 times their original volume. In contrast, Ca-bentonites only swell to twice their original volume (Egloffstein 1995). The larger swell of Na-bentonite is reduced when higher valence cations replace Na^{+}, even in very low concentration environments, effectively converting Na-bentonite into lower swelling capacity and higher hydraulic conductivity bentonites such as Ca-bentonite or Mg-bentonite.

Egloffstein (1995) suggests that even calcium concentrations on the order of 0.0000025–0.015 M in pore water can convert Na-bentonite into Ca-bentonite, provided enough pore volumes of flow pass through the bentonite. Similar behavior can be expected for other divalent cations. This characteristic of bentonite makes GCLs prone to damage by desiccation, particularly in drier regions where the calcium concentration of pore water is high and extensive drying can take place.

Field Performance Studies

The two GCL test sections described in Melchior (1997) were constructed in 1994 to evaluate the performance of GCLs under root penetration, permeation with natural pore water, desiccation, and rehydration. Two needle-punched GCLs were used. The GCLs were placed under 30 cm of topsoil and a 15-cm-thick drainage layer. The topsoil was a sandy loam and

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[1] Geotech. Engr., Kyoto, 619-0237, Japan. E-mail: llin3@yahoo.com

[2] Assoc. Prof., Dept. of Civ. and Envir. Engrg., Univ. of Wisconsin-Madison, Madison, WI 53076. E-mail: chbenson@facstaff.wisc.edu

Note. Discussion open until June 1, 2000. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on September 1, 1998. This paper is part of the *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 126, No. 1, January, 2000. ©ASCE, ISSN 1090-0241/00/0001-0040–0049/ $8.00 + $.50 per page. Paper No. 19149.

the drainage layer was a sand and gravel mixture with 8.8% $CaCO_3$ mineral. A lysimeter was placed beneath the GCLs to collect percolation. No leakage occurred until September 1995, indicating that the GCLs were installed properly. However, excessive leakage did occur during the entire winter of 1995–1996. Exhumation of the GCLs showed that they contained numerous fine cracks that apparently formed during desiccation the previous summer. These cracks did not heal the following winter when rehydration occurred. Melchior (1997) reports that the mineralogical structure of the bentonite was still intact, but that calcium had replaced sodium in the exchange complex and that the swelling capacity decreased to a value close to that typical of Ca-bentonite. Roots were also found to be penetrating through the GCL.

James et al. (1997) used GCLs as roof-sealing materials over five Victorian brick-pillar and arch reservoirs in England. The bentonite component of the GCL was primarily sodium bentonite with 2% calcite. A 30-cm-thick top topsoil layer and a 15-cm-thick gravel drainage layer were installed above the GCL. A layer of clay was placed beneath the GCL. An investigation was conducted after leakage from the roofs was detected. The exhumed GCL samples were evenly swollen, but contained finely cracked zones believed to be responsible for the leakage. Analysis of the bentonite in the GCLs showed that Ca^{2+} had replaced Na^+. The source of calcium was reported to be the calcite in the GCL, and pore water from overlying calcareous soil.

Laboratory Studies

Wet-Dry Cycling

Shan and Daniel (1991) assessed how desiccation affected the hydraulic conductivity of GCLs by conducting hydraulic conductivity tests on a GCL specimen subjected to wet-dry cycling. Tap water from Austin, Tex., was used as the permeant liquid. After four wetting cycles, the GCL retained low hydraulic conductivity ($\sim 1.8 \times 10^{-9}$ cm/s).

Boardman and Daniel (1997) evaluated the effect of desiccation on the hydraulic conductivity of GCLs by conducting desiccation tests in large tanks. An average effective stress of 7.7 kPa was applied during permeation and a total stress of 9.6 kPa was applied during drying. The specimens were hydrated for 3 weeks in the tanks during which a hydraulic conductivity of 1×10^{-9} cm/s was measured. The tanks then were drained and hot-air ventilation was used to dry the GCL in place. A clamp along the sidewalls of the tank restrained the GCL during drying. After the GCL was dried, it was rehydrated for 2 weeks. Cracks formed during desiccation under low total stress. However, the cracks swelled and healed on rewetting, and the GCLs maintained low hydraulic conductivity ($\sim 1 \times 10^{-9}$ cm/s).

Cation Exchange

Shan and Daniel (1991) assessed the compatibility of GCLs permeated with 0.005-M $CaSO_4$, 0.25-M $CaCl_2$, and tap water at low effective stresses (14–35 kPa). All of the specimens were prehydrated with tap water prior to introducing chemical solutions. The hydraulic conductivity of the specimen permeated with 0.25-M $CaCl_2$ increased from 9×10^{-10} (tap water) to 8×10^{-9} cm/s (0.25-M $CaCl_2$). The increase in hydraulic conductivity was attributed to cation exchange, which reduced the thickness of the double layer and increased the effective pore size.

Shackelford (1994) evaluated how calcium solutions affected the hydraulic conductivity of a compacted sand-bentonite mixture (16% bentonite by weight). One specimen was permeated with tap water for two pore volumes ($K = 3.4 \times 10^{-10}$ cm/s), and then a calcium solution was introduced. After five pore volumes, hydraulic conductivity to the calcium solution was 1.7×10^{-9} cm/s. Another specimen was directly permeated with the calcium solution and had a hydraulic conductivity of 2.3×10^{-7} cm/s. Based on these tests, Shackelford (1994) concluded that a specimen first exposed to a chemical solution (or leachate) may not have the same hydraulic conductivity as the same specimen exposed to DI or tap water before exposure to the chemical solution.

Stern and Shackelford (1998) evaluated how $CaCl_2$ solutions affected the hydraulic conductivity of sand-attapulgite-bentonite mixtures having various clay contents. DI water and 0.05-M, 0.1-M, and 0.5-M $CaCl_2$ solutions were used as permeant liquids. For mixtures containing both 10% bentonite and 10% attapulgite permeated directly with $CaCl_2$ solution, the hydraulic conductivity to the $CaCl_2$ was 10–100 times higher than the hydraulic conductivity to DI water, with larger hydraulic conductivity associated with higher $CaCl_2$ concentrations. Hydraulic conductivity approximately 10–20 times lower were obtained when DI water was used as the hydrating fluid before permeation with the $CaCl_2$ solution.

Gleason et al. (1997) performed Atterberg limits tests on Na-bentonite and Ca-bentonite, and hydraulic conductivity tests on thin Na-bentonite and Ca-bentonite layers. Powdered and granular bentonites were used. The Atterberg limit tests showed that increasing the dielectric constant, decreasing the electrolyte concentration, and decreasing the cation valence increased swelling and water retention, which are consistent with the double-layer theory. Thin specimens of Na-bentonite prehydrated with tap water and then permeated with 0.25-M $CaCl_2$ solution maintained low hydraulic conductivity ($\sim 1 \times 10^{-9}$ cm/s), whereas nonprehydrated specimens had hydraulic conductivities about two orders of magnitude higher. A thin layer of Ca-bentonite permeated with tap water and then 0.25-M $CaCl_2$ solution had a hydraulic conductivity of 7×10^{-9} cm/s, which is 23% lower than the hydraulic conductivity of a similar specimen directly permeated with 0.25-M $CaCl_2$ solution.

Quaranta et al. (1997) evaluated cation exchange in the bentonite portion of a GCL. The bentonite was permeated with a mixture of 0.2-M $CaCO_3$ and 0.03-M acetic acid. Effluent analysis showed that Na^+ was initially discharged at a concentration of 1,200 mg/L and subsequently decreased to 5.1 mg/L after 78 pore volumes. The hydraulic conductivity of the bentonite increased dramatically from 4.2×10^{-9} cm/s (1 pore volume) to 4.3×10^{-6} cm/s at 78 pore volumes.

Petrov and Rowe (1997) and Petrov et al. (1997) studied the importance of the first wetting fluid. Tests were conducted using 0.1-M, 0.6-M, and 2.0-M NaCl as permeant liquids and distilled water as the prehydration liquid. Prehydrated GCLs permeated with 0.6-M NaCl had a lower hydraulic conductivity (4.0×10^{-8} cm/s) than GCLs directly permeated with 0.6-M NaCl (5.5×10^{-7} cm/s). The hydraulic conductivity of a prehydrated GCL permeated with 2.0-M NaCl was approximately 2.7×10^{-7} cm/s, which is lower than the hydraulic conductivity of a similar GCL directly permeated with 2.0-M NaCl (2.5×10^{-6} cm/s).

Ruhl and Daniel (1997) permeated GCLs with chemical solutions and leachates. Four different GCLs were tested. Tap water was used as the baseline permeant liquid. When the GCLs were permeated directly with the simulated leachate (0.15-M acetic acid, 0.15-M sodium acetate, 0.007-M salicylic acid, and 0.025-M calcium), the GCLs had hydraulic conductivities between 10^{-6} and 10^{-5} cm/s. Permeation with real leachate resulted in lower hydraulic conductivities (10^{-8}–10^{-10} cm/s). Ruhl and Daniel (1997) concluded that lower hydraulic conductivity was obtained with real leachate because it contained roughly equal amounts of monovalent and polyvalent cations, and the monovalent cations apparently offset the effects of the polyvalent cations. Two GCLs prehydrated with tap water and then permeated with simulated MSW leachate were also studied. GCLs prehydrated in tap water had hydraulic conductivities about four orders of magnitude lower than GCLs directly permeated with synthetic leachate.

MATERIALS

GCLs

A needled-punched GCL containing loose granular Na-bentonite was used in this study. The Na-bentonite was sandwiched between a silt-film monofilament woven geotextile (mass per unit area 170 g/m^2) and a staple-fiber nonwoven geotextile (mass per unit area 206 g/m^2). The dry mass per unit area of the GCL was 7.5 kg/m^2.

The mineralogy of the bentonite in the GCL was analyzed using X-ray diffraction. The bentonite contained 67% montmorillonite, 10% quartz, 7% cristobalite, 11% plagioclase feldspar, 5% potassium-feldspar, and a trace of illite and mica.

Pore Water and Permeant Liquids

Pore-water extractions were conducted to determine the ionic strength of pore water in a surface layer that may be placed on landfill covers. Topsoil was obtained from five areas on the University Wisconsin-Madison campus and four areas on a Madison area landfill at a depth of 127–254 mm below ground surface. Because the soil was not sufficiently wet to squeeze out pore water, each 100-g soil sample was mixed with 100 mL of DI water for at least 16 h. Pore-water extracts obtained for soaking periods greater than 16 h had essentially the same electrical conductivity as that from soils soaked for 16 h. After soaking, the soil-pore water mixture was separated using a centrifuge. The supernatant was then decanted and an electrical conductivity probe was used to measure the electrical conductivity of the diluted pore water. The electrical conductivity of the pore water EC_p was then calculated using (1)

$$EC_p = EC_m\left(\frac{V_p + V_d}{V_p}\right) \tag{1}$$

where EC_m = electrical conductivity of the diluted pore water (mS/cm); V_p = volume of pore water (mL); and V_d = volume of DI water that was added (mL). The ionic strength of the pore water (I, M) was estimated using (2) (Griffin and Jurinak 1973)

$$I \cong 0.013EC_p \tag{2}$$

The electrical conductivity of the nine specimens ranged between 0.67 and 3.16 mS/cm, and averaged 1.36 mS/cm at room temperature (23°C). The corresponding ionic strengths range between 0.0087 and 0.0412 M, and average 0.0165 M. The pH of the pore water was typically neutral (6–7), and was not affected by the DI water added.

Three different permeant liquids, DI water (pH 6.5), tap water (pH 6.8), and 0.0125-M $CaCl_2$ solution (pH 6.2), were used to span the range of pore-water ionic strengths that may contact a GCL in a cover. DI water ($EC \sim 0.0005$ mS/cm at 23°C) was used as the control. Tap water ($EC \sim 0.59$ mS/cm at 23°C) was used to simulate prehydration water in the field that might be present shortly after construction due to rainwater. The calcium chloride solution (0.0125 M, $EC \sim 2.0$ mS/cm, $I \sim 0.026$ M, pH 6.2 at 23°C) has a similar electrical conductivity ($\sim$1.36 mS/cm at 23°C), and pH ($\sim$6.5) as the average pore water of the soil specimens. $CaCl_2$ was selected to represent the predominance of divalent cations (e.g., Ca^{2+}, Mg^{2+}) observed in natural pore waters (Bohn et al. 1985). The cations in the water extracts collected in this study were also predominantly divalent. Analysis of the pore water showed that cation concentrations ranged between 0.025–0.0084 M for Ca^{2+}, 0.019–0.0034 M for Mg^{2+}, 0.00114–0.0035 M for K^+, and 0.016–0.002 M for Na^+, and averaged 0.0167 M for Ca^{2+}, 0.0112 M for Mg^{2+}, 0.00225 M for K^+, and 0.009 M for Na^+ at near neutral pH ($\sim$6.5).

The extraction method that was employed tends to slightly overestimate cation concentrations (Iyer 1990). However, the cation concentrations are believed to be representative of average conditions in the United States because the specimens were collected after infiltration events, which depress cation concentrations. Moreover, Madison is a humid location. Significantly higher concentrations of divalent cations are usually found in the drier portions of the United States (Sposito 1989).

METHODS

Atterberg Limits

Atterberg limit tests were performed initially on specimens of bentonite and after each drying cycle. The tests were conducted according to ASTM D 4318, except the mixing fluid was DI water, tap water, or the 0.0125-M $CaCl_2$ solution. After the Atterberg limits were measured, the bentonite was air-dried until the loss of water ceased. The dry bentonite was then ground back to its original aggregate size distribution by matching the aggregate size distribution of the dried and crushed bentonite to that of the original dry bentonite (Lin 1998). The tests were then repeated using the same procedure. Each specimen went through five wetting and drying cycles.

Swell Tests

Swell tests were performed using Geosynthetic Research Institute (GRI) GCL-1, except plastic molds were used. The steel molds described in GCL-1 were used in an initial series of tests. Rust formed on the molds, which may have influenced the character of the bentonite. Consequently, a PVC tube 100 mm in diameter and 178 mm long was used instead of the 152-mm-diameter steel mold described in GRI GCL-1.

The test apparatus is shown in Fig. 1. The base of the container was a perforated PVC plate with 15 1.6-mm-diameter holes uniformly spaced over the plate within a 50-mm-radius of the center of the plate. The loading plate was acrylic and had a diameter of 98 mm, and 20 evenly spaced 1.6-mm holes. An acrylic stem was attached to the loading plate for measuring swell. Glass beads were placed on top of the porous plate to increase the surcharge to 528 g, which yields the 0.68-kPa

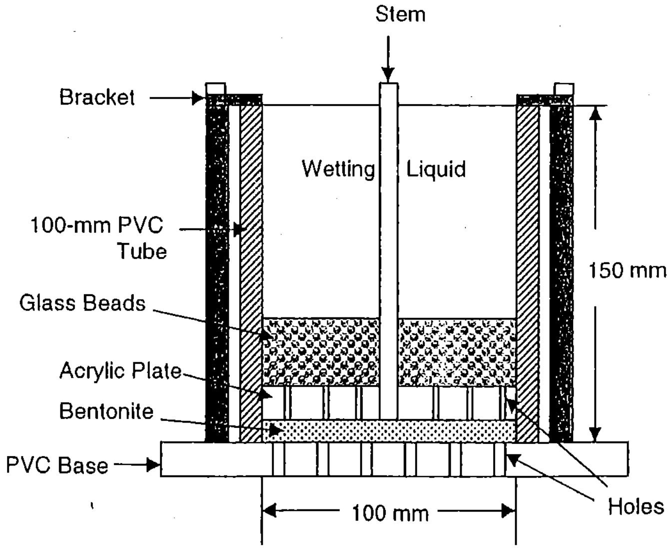

FIG. 1. Swell Test Apparatus

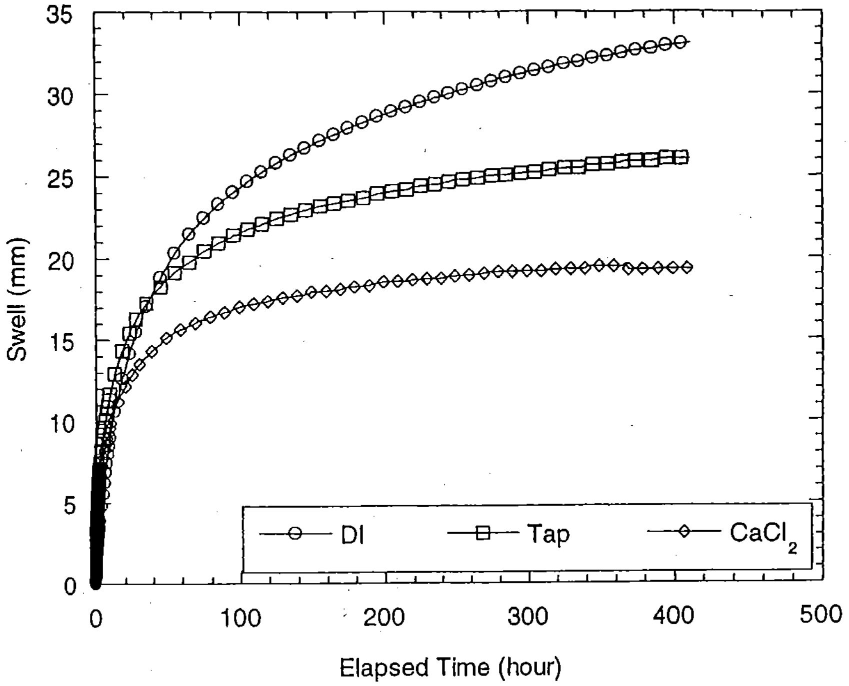

FIG. 2. Typical Swell Curves

applied stress required in GCL-1. A linear variable differential transformer attached to a computer was used to measure swell during hydration. A plastic container was used to hold the test apparatus and the inundation liquid.

Tests were set up using DI water, tap water, and a 0.0125-M $CaCl_2$ solution with 100 g of dry bentonite (~8 mm thickness). Typical swell curves obtained with the apparatus are shown in Fig. 2. GRI GCL-1 calls for reporting the swell at 24 h. However, swelling continued at a significant rate at the 24-h termination point, and at 400 h equilibrium was still not established. However, the rate of swell diminished substantially by 400 h, indicating that equilibrium was nearly achieved. Thus, a 400-h swell time was used for all tests.

Additional swell tests were conducted after various cycles of wetting and drying. Once the initial 400-h swell period was achieved, the bentonite was removed from the swell mold and air-dried at room temperature. The weight of the bentonite was measured daily while air-drying. When the weight stopped decreasing, the bentonite was ground back to its original aggregate distribution as closely as possible. The bentonite was then rehydrated in the swell mold for another 400 h. At the end of 400 h, the bentonite was air-dried again and the process repeated.

Hydraulic Conductivity Tests

Trimming

Key issues in trimming GCLs are bentonite loss along the edges of the GCL and pinching of the geotextiles (Daniel et al. 1997). The trimming procedure used in this study was designed to minimize these effects.

A steel trimming ring 150 mm in diameter with a sharp edge was pushed down and slowly rotated on a 200 mm × 200 mm sample of GCL. The ring was tightly pressed into the upper and lower geotextiles without grabbing or twisting the geotextiles during rotation. The GCL was then cut along the outer edge of the trimming ring using a utility knife with a new blade. After cutting, a thin stream of permeant water was sprayed along the interface of the trimming ring and GCL. The specimen was then left to hydrate for several minutes. After hydration, the trimming ring was gently lifted while holding down the GCL specimen.

Trimmed specimens were inspected for bentonite loss and pinching of the geotextiles. When bentonite fell out from the edges, bentonite paste (a bentonite and permeant water mixture) was lightly added between the geotextiles. Geotextiles that were pinched were separated using a spatula and excess fibers were trimmed with scissors. The edge of the GCL specimen was also checked for roughness that might result in a preferential flow path.

Permeation

GCLs in covers can desiccate during dry seasons (spring and summer) and rehydrate again during rainy seasons (autumn and winter) (Melchior 1997). To simulate this cyclic behavior, specimens were permeated for 1 month and then air-dried in the laboratory, which has a relative humidity of approximately 50%. The tests were conducted in flexible-wall permeameters following GRI GCL-2. An average effective confining stress of 17.5 kPa was applied to simulate a cover with a 60-cm-thick surface layer and 30-cm-thick drainage layer above the GCL. The hydraulic gradient was 80.

The permeant liquids used were DI water, tap water, and the 0.0125-M $CaCl_2$ solution. Tests were terminated after the hydraulic conductivity was steady, at least 1 month elapsed, and after at least four consecutive readings of outflow/inflow were between 0.75 and 1.25. After the tests were terminated, the specimens were air-dried on a bench until the weight of the GCL specimen became constant. The specimens then were permeated again using the same procedure.

The minimum permeation time of 1 month was used to simulate flow through a GCL during the winter months, when flow through barrier layers normally occurs (Khire et al. 1997; Melchior 1997). One month of permeation at a hydraulic gradient of 80 roughly corresponds to nearly 3 months of flow at a hydraulic gradient of 30, which would occur if the drainage layer was saturated.

One specimen was permeated with DI water for five wetting cycles. Another specimen was permeated with the 0.0125-M $CaCl_2$ solution for six wetting cycles. The other specimens were wetted with DI water or tap water during the first cycle and 0.0125-M $CaCl_2$ during subsequent wetting cycles (up to eight cycles). The tests conducted initially with DI water and then with the $CaCl_2$ solution were used to evaluate the effect of the first wetting liquid on the hydraulic conductivity of the GCL. For example, a GCL might become hydrated with rainwater after installation. For the specimens permeated with 0.0125-M $CaCl_2$, a bladder accumulator (Daniel 1994) was used to protect the pressure panel from contamination. No replicate tests were conducted due to the length of time required to complete each set of tests and limitations on the availability of equipment.

RESULTS

Atterberg Limit Tests

The liquid limits (LL) and plasticity indices (PI) are summarized in Fig. 3. The LL and PI are highest for the bentonite mixed with DI water and lowest for the bentonite mixed with the 0.0125-M $CaCl_2$ solution, which is consistent with double-layer theory and the results reported by Gleason et al. (1997). The LL and PI of bentonite mixed with DI water increase after each wet-dry cycle, but at a decreasing rate. Some Na^+ ions (as well as other soluble salts) are "washed-out" during each wet-dry cycle, as water containing cations is lost from the bentonite during testing. As a result, the salt concentration decreases, the thickness of the double layer increases, and the soil becomes more plastic.

For the samples mixed with tap water or the 0.0125-M $CaCl_2$ solution, the LL and PI decrease after each wetting and drying cycle. Tap water from Madison contains a large quantity of Ca^{2+} (0.004 M) and Mg^{2+} (0.0017 M), as well as K^+ (0.000022 M), Na^+ (0.00035 M), and Cu^+ (0.0000047 M). The divalent cations replace the Na^+, reducing the double-layer thickness and the plasticity of the bentonite. Hydrating the bentonite with the $CaCl_2$ solution has a similar but more pronounced effect.

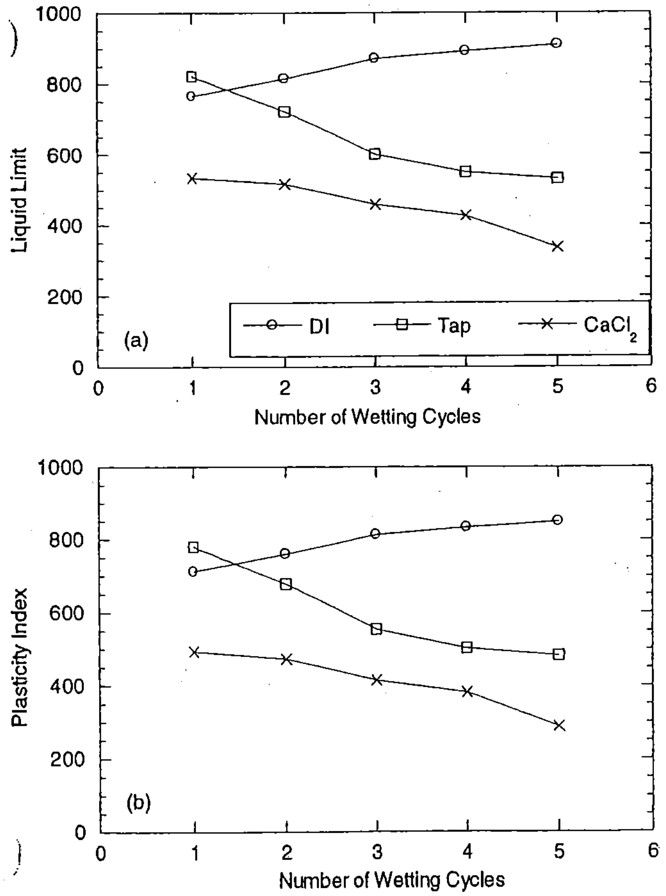

FIG. 3. (a) Liquid Limit; (b) Plasticity Index as Function of Number of Wetting Cycles

Although the LL and PI decreased substantially due to wet-dry cycling with tap water and 0.0125-M $CaCl_2$, they are far higher than the LL and PI reported for Ca-bentonite. For example, Gleason et al. (1997) reported that the LL and PI of Ca-bentonite are 124 and 98, respectively, when DI water is used for mixing. Thus, greater reductions in plasticity should occur as the number of wet-dry cycles increases.

Swell Tests

Results of the initital swell tests conducted with DI water, tap water, and 0.0125-M $CaCl_2$ are shown in Fig. 2, and they are consistent with the double-layer theory. The bentonite hydrated with DI water swelled the most (Fig. 2), whereas the bentonite hydrated with 0.0125-M $CaCl_2$ swelled the least. The 400-h swell for tap water falls between that for DI water and $CaCl_2$ solution because of its intermediate ionic strength (0.0087 M for tap water versus 0.0125 M for $CaCl_2$).

Results of the swell tests conducted on bentonite subjected to wet-dry cycling are shown in Fig. 4. The data marked "DI-$CaCl_2$" and "Tap-$CaCl_2$" correspond to tests where the initial wetting liquid was DI water or tap water, and 0.0125-M $CaCl_2$ was used for subsequent wettings. The bentonite hydrated with the 0.0125-M $CaCl_2$ solution has the least amount of swell during the first wetting cycle, and the swell decreases in subsequent cycles. The greatest swell was obtained for DI water, followed by tap water. In addition, the swell did not decrease with wet-dry cycling when the wetting liquid was DI water or tap water.

For the DI-$CaCl_2$ specimen, first wetting with DI water resulted in 29 mm of swell. The swell dropped after the second cycle, where $CaCl_2$ solution was used. However, swell in the second cycle (26.2 mm) was still greater than swell in the first cycle for the specimen initially hydrated with tap water [Tap-$CaCl_2$ (25.5 mm), Fig. 4]. Swell of the DI-$CaCl_2$ specimen was much smaller during the third (19 mm), fourth (12.3 mm), and fifth (6.9 mm) cycles.

Similar behavior was exhibited by the Tap-$CaCl_2$, specimen. This specimen swelled approximately 26 mm in the first and second cycles, but the swell decreased to 17 mm in the third cycle and then dropped to 2.2 mm in the fourth wetting cycle. Essentially, the same swell occurred in the fifth cycle (3 mm).

The temporal behavior of the swell tests is illustrated in Fig. 5 for the $CaCl_2$, DI-$CaCl_2$, and Tap-$CaCl_2$ tests. During the

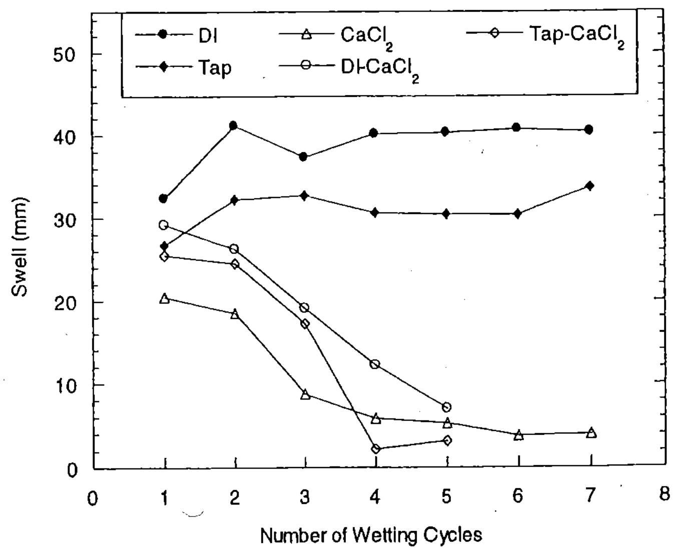

FIG. 4. Amount of Swell at Each Wetting Cycle

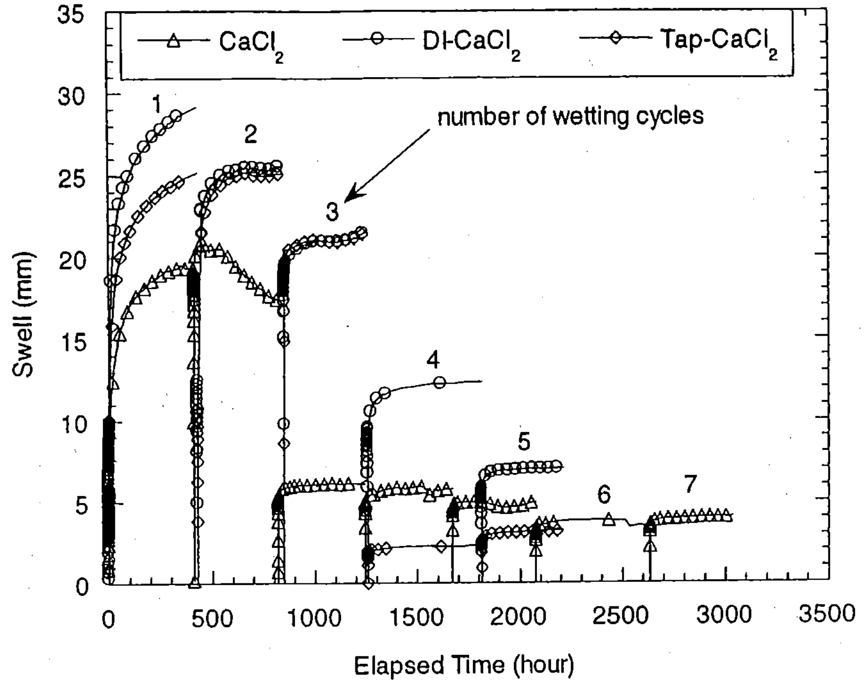

FIG. 5. Temporal Behavior of Swell Tests at Various Wet-Dry Cycles

first wetting, swell occurs over an extended period of time. Swell ceases more quickly in the subsequent cycles and, in one case, swell was followed by consolidation. In Cycle 2, the bentonite initially and subsequently hydrated with 0.025-N $CaCl_2$ ($CaCl_2$ in Fig. 5) swelled 21 mm (66 h), and then consolidated to 17 mm. In subsequent cycles, the $CaCl_2$ specimen only swelled to around 5 mm.

The results for the swell tests conducted directly with the $CaCl_2$ solution suggest that most of the exchange for Na^+ occurs within two wetting cycles, during which the Na-bentonite is essentially converted to Ca-bentonite. Similar results are reported by Egloffstein (1995). He shows that 2 g of Na-bentonite can swell to over 30 mL when submerged in 100 mL of distilled water for 48 h, whereas Ca-bentonite swells to only 5–7 mL under the same conditions. That is, Na-bentonite swells about six times more than Ca-bentonite, which is similar to the ratio of the initial swell relative to that after three wetting cycles in $CaCl_2$ as shown in Fig. 4 (i.e., 32 mm ÷ 5 mm = 6.4). In addition, Egloffstein (1995) shows that Ca-bentonite absorbs water very rapidly, the process being practically complete after approximately 15–30 min, which is also evident in the swell curves for cycles 3–6 (Fig. 5).

An initial exposure to a water with lower ionic strength (e.g., DI or tap water) delays this behavior, but only temporarily. Within three to five cycles, Na-bentonite exposed initially to dilute waters and subsequently with 0.0125-M $CaCl_2$ lost most of its swell capacity.

A similar effect should be observed in covers, where pore water rich in divalent cations may permeate the GCL during the wetter winter months, followed by drying in the summer months. Each year the bentonite will become less plastic and more brittle, and will swell less when rehydrated. As a result, the bentonite will become more permeable either due to larger effective pore spaces caused by shrinkage of the double layer or flow through cracks that do not swell shut during rehydration.

Hydraulic Conductivity Tests

Results of hydraulic conductivity tests conducted on GCL specimens subjected to wetting and drying are summarized in Table 1 and Fig. 6. All of the specimens had low hydraulic conductivity during the first three wetting cycles. The hydraulic conductivity of the specimen permeated initially and subsequently with $CaCl_2$ ($CaCl_2$ specimen) decreased during the first three cycles, which may have been due to osmotic effects. These low hydraulic conductivities can be primarily attributed to the large swelling capacity of the bentonite. When dry, the specimens contained large cracks (Fig. 7) that swelled shut during rehydration.

During the fourth cycle, the hydraulic conductivity of the $CaCl_2$ and Tap-$CaCl_2$ specimen increased slightly. In the fifth and sixth cycles, the hydraulic conductivity of these specimens increased more than an order of magnitude. The test setup was examined for signs that sidewall leakage could be the cause of the high hydraulic conductivities, but no evdience of a short circuit was found. In addition, a light red dye was added to the permeant liquid to mark the flow path. Inspection of the specimens revealed dye-stained cracks in the bentonite, suggesting that flow was passing preferentially through cracks that formed during drying and did not heal on rehydration. Cracks in a dried specimen permeated with $CaCl_2$ are shown in Fig. 8.

The specimen initially permeated with DI water and subsequently with 0.0125-M $CaCl_2$ maintained low hydraulic conductivity through six wetting cycles. During the seventh cycle, however, the hydraulic conductivity increased one and one-half orders of magnitude. Another large increase in hydraulic

TABLE 1. Summary of Hydraulic Conductivities of GCL Specimens

Number of wetting cycles (1)	Permeant			
	DI (cm/s) (2)	$CaCl_2$ (cm/s) (3)	DI-$CaCl_2$ (cm/s) (4)	Tap-$CaCl_2$ (cm/s) (5)
1	1.2×10^{-9}	3.8×10^{-9}	1.6×10^{-9}	1.7×10^{-9}
2	2.4×10^{-9}	1.2×10^{-9}	1.4×10^{-9}	1.5×10^{-9}
3	1.9×10^{-9}	6.4×10^{-9}	1.3×10^{-9}	1.8×10^{-9}
4	2.2×10^{-9}	4.4×10^{-9}	1.0×10^{-9}	4.7×10^{-9}
5	2.9×10^{-9}	2.8×10^{-7}	1.1×10^{-9}	2.1×10^{-7}
6	—	7.6×10^{-6}	1.2×10^{-9}	3.9×10^{-6}
7	—	—	4.6×10^{-7}	—
8	—	—	5.8×10^{-6}	—

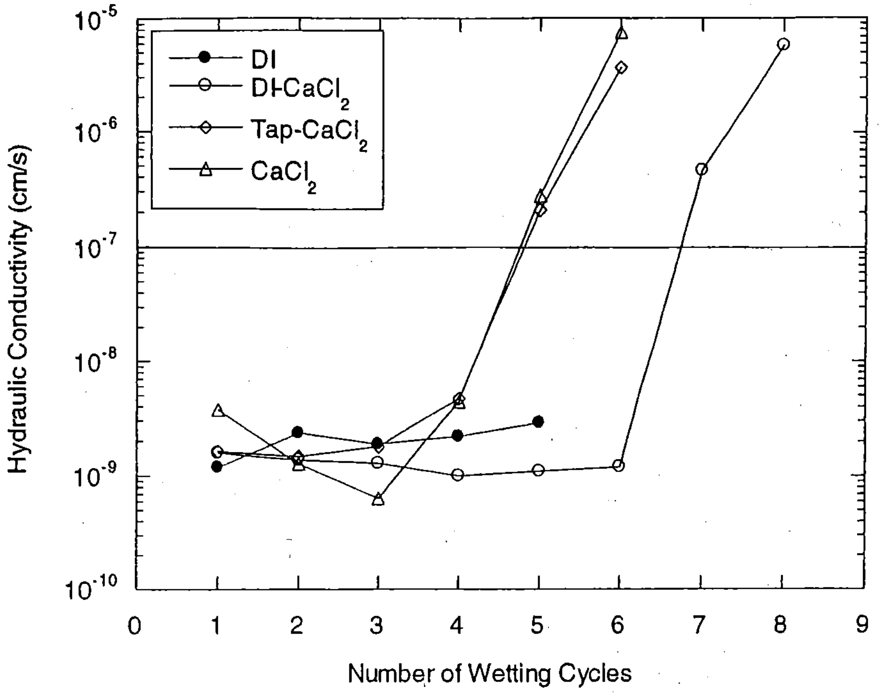

FIG. 6. Hydraulic Conductivity at Each Wetting Cycle

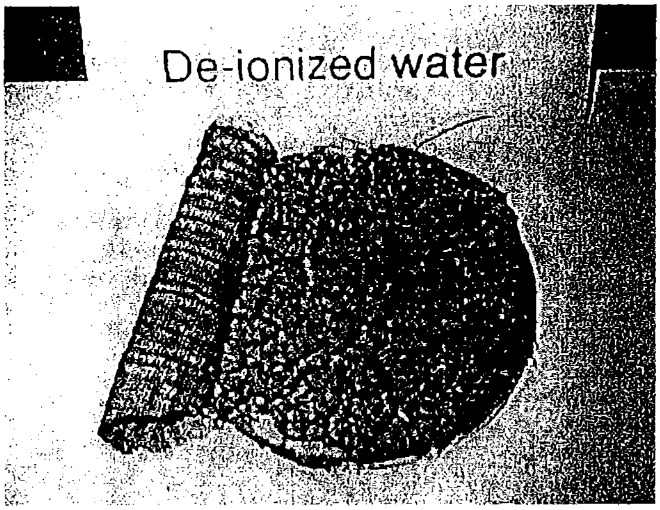

FIG. 7. Specimen Permeated with DI Water Showing Desiccation Cracks from Drying after Third Wetting

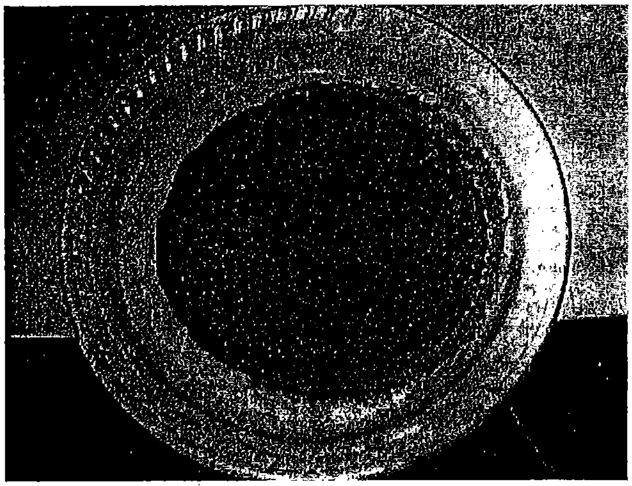

FIG. 8. Tap-$CaCl_2$ Specimen Showing Desiccation Cracks from Drying after Sixth Wetting

conductivity was also observed during the eighth cycle. Dye testing of this specimen also showed that flow was primarily passing through cracks in the bentonite. Thus, as with the swell tests, first exposure to a dilute water can delay but not prevent the detrimental effects of Ca^{2+} exchange. In contrast, the specimen that was always permeated with DI water maintained its low hydraulic conductivity. Swelling of the bentonite closed the cracks that formed during drying, preventing preferential flow.

Cracking induced by desiccation was clearly responsible for the large increase in hydraulic conductivity. Similar increases in hydraulic conductivity would not occur during the same time frame had the specimen remained saturated. For example, one specimen was continually permeated for 9 months during the study period with 0.0125-M $CaCl_2$ (i.e., no drying), and it retained low hydraulic conductivity ($\sim 1.1 \times 10^{-9}$ cm/s) (Fig. 9). More than eight pore volumes of 0.0125-M $CaCl_2$ passed through the specimen. In contrast, the hydraulic conductivity

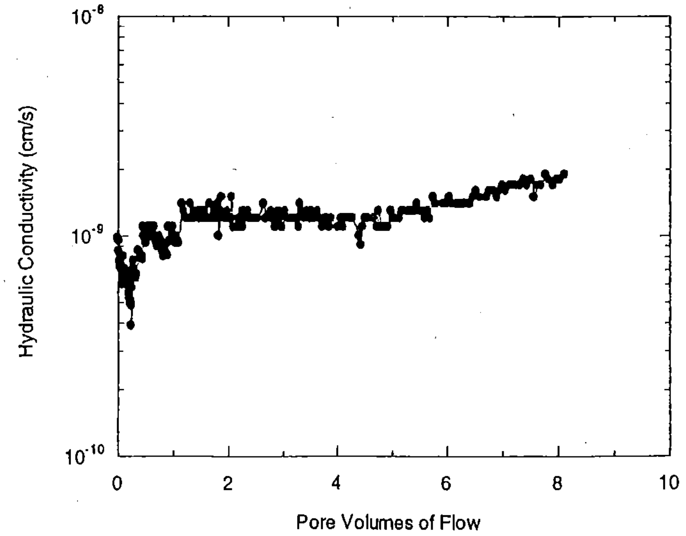

FIG. 9. Specimen Continuously Permeated with 0.0125-M $CaCl_2$ Solution

of the specimen permeated with 0.0125-M $CaCl_2$ and subjected to drying increased two orders of magnitude within only three pore volumes of permeation. The specimen that was never dried retained low hydraulic conductivity because no cracks formed in the specimen.

The results obtained in this study differ from those in Shan and Daniel (1991) and Boardman and Daniel (1997) because the GCLs tested in this study were exposed to more wet-dry cycles (five to seven cycles) and to stronger solutions. Shan and Daniel (1991) exposed GCL specimens to three to four wetting cycles, and Boardman and Daniel (1997) used two wetting cycles. The 0.0125-M $CaCl_2$ solution used in this study had a significantly higher concentration of divalent cations than the Austin tap water used by Shan and Daniel (1991) and Boardman and Daniel (1997). Eykholt (1988) reports that Austin tap water contains 0.0004- to 0.00055-M Ca^{2+} and 0.00075-M Mg^{2+}. Tests on Austin tap water conducted at the University of Wisconsin showed 0.00036-M Ca^{2+} and 0.00064-M Mg^{2+}. In contrast, Madison tap water contains 0.002-M Ca^{2+} and 0.0017-M Mg^{2+}. The GCL specimens were also permeated for a longer time in this study. Boardman and Daniel (1997) used 3 weeks for the first wetting and 2 weeks for the second wetting, whereas 1 month was used in this study.

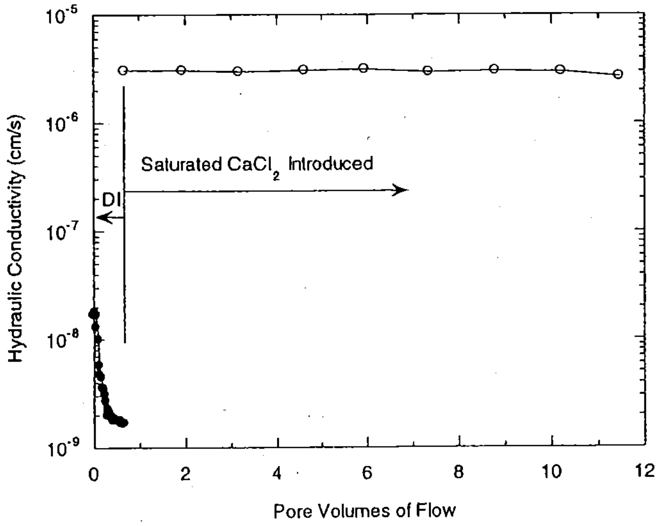

FIG. 10. GCL Specimen Permeated with DI Water, Dried, and then Permeated with Saturated $CaCl_2$ (6.7 M) Solution

An additional test was conducted to determine if increases in hydraulic conductivity would occur within a fewer number of wetting cycles if the ionic strength of the pore water was stronger. To evaluate the worst-case condition, a GCL specimen was initially permeated with DI water for 1 month and then dried following the procedures used for the other specimens. After drying, the specimen was permeated with a saturated $CaCl_2$ solution (6.7 M, pH 6.2). Results of these tests are shown in Fig. 10. The hydraulic conductivity to DI water was very low ($\sim 2 \times 10^{-9}$ cm/s). In contrast, the hydraulic conductivity after drying and permeation with the 6.7-M $CaCl_2$ solution was 3×10^{-6} cm/s. The high hydraulic conductivity obtained on rewetting was caused by the cracks that formed during drying that did not swell shut when the GCL was rehydrated using 6.7-M $CaCl_2$. The implication of this finding is that increases in hydraulic conductivity may occur in fewer cycles if the pore water has higher ionic strength and predominately divalent or multivalent cations, as might occur in drier regions.

The changes in hydraulic conductivity shown in Fig. 6 are also consistent with changes in GCL thickness that occurred during wet-dry cycling (Fig. 11). For the specimens permeated with 0.0125-M $CaCl_2$, the GCL thickness gradually decreased as the number of wetting cycles increased, most likely as a result of Ca^{2+} being exchanged for Na^+. The greatest changes in thickness occurred after the third wetting cycle. After the sixth wetting cycle the hydrated GCL thickness was lower than the initial dry thickness of the GCL for the $CaCl_2$ and Tap-$CaCl_2$ specimens. Moreover, the large drop in thickness that occurred after the fourth wetting coincided with the initiation of increasing hydraulic conductivity, as shown in Fig. 6.

In contrast, the thickness of the specimen permeated with DI water initially remained the same and then increased during wet-dry cycling. The thickness increased to 16 mm after the fourth wetting and 21 mm after the fifth wetting because the needle-punching fibers pulled out, which permitted additional

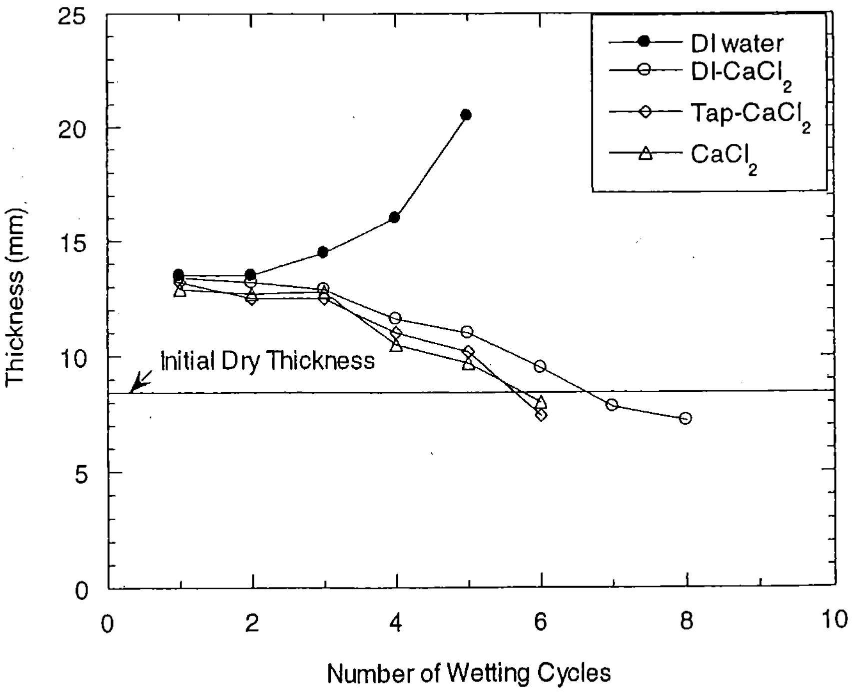

FIG. 11. Thickness of GCL Specimens after Various Wetting Cycles

swell. This specimen experienced no measurable change in hydraulic conductivity.

The results of the hydraulic conductivity tests are consistent with those from the index tests. That is, the specimens hydrated or permeated with $CaCl_2$ lost plasticity and swell capacity, and their hydraulic conductivity increased due to formation of cracks. These changes occurred faster for the specimens permeated initially with $CaCl_2$ solution. Nevertheless, changes in the bentonite occurred regardless of whether the GCLs were initially hydrated with other liquids (i.e., DI water or tap water).

PRACTICAL IMPLICATIONS

The results of this study are consistent with the field results reported by Melchior (1997) and James et al. (1997). After several wet-dry cycles, cracks that form in GCLs during desiccation do not heal during rehydration because of reduced swell capacity caused by cation exchange. In the field, divalent cations were exchanged for Na^+, which prevented desiccated and cracked GCLs from healing during rehydration. Larger than expected leakage rates in the field were attributed to flow through these cracks.

The practical implication of these results is that GCLs must be used with great care in environments where desiccation of the GCL may occur. This is particularly true in semiarid regions such as cool deserts. In such locations, barrier soils often become saturated in the winter months and very dry in the summer months (Khire et al. 1997; Nyhan et al. 1997; Ward and Gee 1997). Pore water in these environments also tends to have higher salt concentrations than those in more humid climates (Sposito 1989). However, care must also be used in more humid climates, such as in the United Kingdom and Germany, where GCLs failures have occurred, and in the eastern United States where clay barriers have been found to be extensively cracked by desiccation (Montgomery and Parsons 1990; Benson and Khire 1995). The safest approach is to cover the GCL with a geomembrane (i.e., as in a composite barrier), and to ensure that sufficient surcharge overburden is placed above the geomembrane and GCL to maintain good interfacial contact. Field studies by Corser and Cranston (1990) indicate that a 0.6-m-thick surface layer provides sufficient surcharge to maintain contact and prevent desiccation.

SUMMARY AND CONCLUSIONS

The purpose of this study was to evaluate how exposure to pore water containing divalent cations at natural concentrations affects the plasticity and swelling of bentonite and the hydraulic conductivity of GCLs subjected to wet-dry cycling. Atterberg limits and free swell tests were performed to assess how plasticity and swell are affected by wet-dry cycling. Hydraulic conductivity tests were conducted on GCL specimens exposed to six to eight wetting and drying cycles using different wetting liquids.

The Atterberg limit tests showed that the plasticity of the bentonite continually decreased with an increasing number of wet-dry cycles when tap water or 0.0125-M $CaCl_2$ was used for wetting. In contrast, the plasticity increased with wet-dry cycling when the specimen was wetted with DI water. Apparently, excess Na^+ was lost when DI was used for wetting, which resulted in a lower salt concentration, a greater double-layer thickness, and greater plasticity. In the other tests, Ca^{2+} or other divalent cations apparently exchanged for Na^+, resulting in a thinner double layer and lower plasticity.

Similar results were obtained from the swell tests. Similar or greater swell was obtained with wet-dry cycling when DI or tap water was used for wetting. Large reductions in swell were obtained with wet-dry cycling when 0.0125-M $CaCl_2$ was used for wetting. Within four or five wet-dry cycles, swell in 0.0125-M $CaCl_2$ was very small and no longer decreased with additional wet-dry cycles. Initial exposure to DI or tap water temporarily delayed the reductions in swell. However, ultimately all of the bentonites wetted with 0.0125-M $CaCl_2$ lost their swelling capacity.

All of the GCL specimens had low hydraulic conductivity ($\sim 1 \times 10^{-9}$ cm/s) during the first three wetting cycles. The hydraulic conductivity of specimens initially hydrated in tap water or 0.0125-M $CaCl_2$ and subsequently in 0.0125-M $CaCl_2$ increased slightly after the fourth wetting ($\sim 4 \times 10^{-9}$ cm/s), and then increased dramatically during the fifth ($\sim 2-3 \times 10^{-7}$ cm/s) and sixth ($\sim 4-8 \times 10^{-6}$ cm/s) wettings. Similarly, the specimen initially permeated with DI water and subsequently with 0.0125-M $CaCl_2$ maintained low hydraulic conductivity through the sixth wetting; however, its hydraulic conductivity increased dramatically to 4.6×10^{-7} cm/s during the seventh wetting and to 5.8×10^{-6} cm/s during the eighth wetting. These large increases in hydraulic conductivity were caused by preferential flow through desiccation cracks that did not heal on rehydration. In contrast, the specimen wetted with DI water maintained low hydraulic conductivity regardless of the number of wet-dry cycles.

The changes in hydraulic conductivity corresponded closely with changes in thickness of the GCLs. The thickness of the specimen permeated only with DI water remained the same or increased during each wetting cycle. In contrast, the hydrated thickness of the specimens permeated with 0.0125-M $CaCl_2$ decreased during each wetting, eventually dropping below the initial dry thickness of the GCL.

Desiccation cracking was clearly responsible for the increases in hydraulic conductivity. One GCL specimen was permeated throughout the study with 0.0125-M $CaCl_2$, and maintained low hydraulic conductivity, even though it was permeated with six pore volumes of $CaCl_2$ solution. In addition, increases in hydraulic conductivity may occur more quickly than observed in this study if the pore water contains a higher concentration of divalent cations. For example, a large increase in hydraulic conductivity occurred after one desiccation cycle for a specimen initially permeated with DI water, then dried and rewetted with a concentrated (6.7-M) $CaCl_2$ solution.

These findings suggest that the hydraulic conductivity of GCLs exposed to wet-dry cycles with waters having a higher concentration of divalent cations eventually will increase due to the inability of the bentonite to heal desiccation cracks. These results are consistent with two field studies (James et al. 1997; Melchior 1997), showing that desiccation cracks in GCLs did not heal on rewetting. As a result, GCLs may not be effective hydraulic barriers if they are allowed to wet and dry in the presence of natural pore waters containing primarily divalent cations. From a practical perspective, this implies that GCLs must be used with great care in environments where they may undergo wet-dry cycling with such pore waters.

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Bentonite as sealing material in geosynthetic clay liners – Influence of the electrolytic concentration, the ion exchange and ion exchange with simultaneous partial desiccation on permeability

T.A. Egloffstein
ICP International Consulting Prof. Czurda & Partners, Karlsruhe, Germany

ABSTRACT: Geosynthetic clay liners (GCLs) are sealing layers, which usually contain natural sodium bentonite as a effective sealing element, which is encapsulated between geotextile components. They are used in a variety of sealing applications, predominantly in hydraulic engineering and groundwater protection. They are most commonly employed to replace compacted clay liners (CCLs). In contact with water, bentonites swell and thereby close their pore spaces, which accounts for their low permeability. This extreme swelling requires water with a low content of electrolytes. Contact with chemicals in leachates and other solutions can lower the swelling of a GLC and thereby lead to a higher permeability. Commonly GCLs are covered with soil to create counter pressure against the swelling process in order to receive a denser structure with low hydraulic permeability. Besides this, the soil cover protects the GCL against damaging. In this geo-chemical environment an ion exchange of sodium-bentonite to calcium-bentonite occurs due to two reasons. Firstly calcium is often predominating, secondly bivalent Ca^{2+} is more easily exchanged against monovalent sodium (Na^+) than vice versa. This exchange typically takes place over a period of several month to few years, if in contact with cover-soil seepage. The ion exchange effects an increase in hydraulic conductivity of approximately ½ to 1 decimal exponent. This is however not alarming, as long as planning engineers take this effect into consideration. Landfill capping systems as well as sealings along highways through water protection areas are characterized by unsaturated conditions, as often found in applications with low confining stress ($<15\,kN/m^2$, less than 0.75 m soil-cover). In such cases, GCLs tend to show desiccation cracks, which cause a significant increase in permeability. In contrast to compacted clay liners, where self sealing is unlikely to occur due to low confining stress, a self sealing of calcium-bentonite GCLs takes place by swelling and plastification of bentonite, if a soil-cover of more than 0.75, better 1.0 m (equals a confining stress of 15–20 kN/m^2) is provided.

1 INTRODUCTION

Central part of a GCL, is of course the layer of bentonite which is held in between carrier layers of geotextiles. The sealing material in geosynthetic clay liners (GCLs), -natural sodium bentonite-, is a naturally occurring clay with extraordinary properties, such as very high expansion capability by absorbing water (swelling capacity), high ion-exchange capacity and very low water permeability. Bentonites occur largely as the product of weathering, through a chemical transformation from acid volcanic glass tufa (volcanic ashes) which have been deposited in the sea (Na-bentonites) or in fresh water (Ca-bentonites). Typical properties of sodium bentonite in GCLs are shown in Table 1.

High-quality bentonites like those used in GCLs mainly consist of the three-layered (2:1) clay mineral montmorillonite (approx. 75–90% of their weight). The excellent properties of bentonite are exclusively attributed to the properties of the swellable clay mineral montmorillonite. The individual clay mineral crystal of the montmorillonite ideally consists of 5 to 15 flake-like silicate layers, most of the flakes having a tortuous, irregularly curved shape. A flake-like clay mineral crystal of approx. 15 silicate layers has a thickness of nearly 15–20 nm and a side length of approx. 0.2–2 µm.

GCLs are manufactured by placing powdered or granulated bentonite on a geotextile. The bentonite layer is typically 4 to 10 mm thick and is placed at a mass per unit area of 4 to 10 kg/m^2; a typical unit weight is 4.5 kg/m^2. GCLs are manufactured with a cover and a carrier geotextile to encapsulate the bentonite. The

Table 1. Typical properties of sodium bentonites in GCLs.

montmorillonite content (methylenblue-method)	75–90%
water absorption capacity (Enslin/Neff)	550–700 weight%
Swelling volume (ASTM D 5890-95)	25–30 ml
ph-value (suspension)	9–10.5
plasticity (Ip)	140–380%
friction angle (φ) / cohesion (c)	3–7°/3–5 kN/m^2
permittivity (Ψ)	$1\text{–}5 \cdot 10^{-9}$ l/s
hydraulic conductivity (k)	$1\text{–}5 \cdot 10^{-11}$ m/s
cation exchange capacity (CEC)	60–90 mmol(eq)/100 g

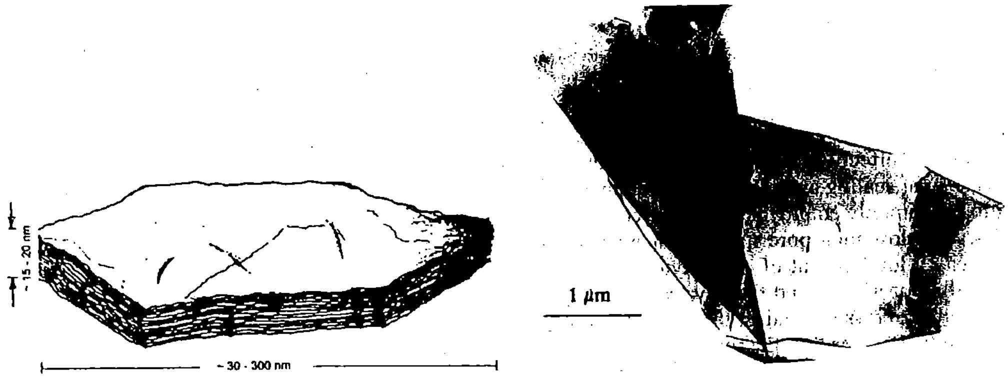

Figure 1. Calcium-montmorillonite with approximately 15 silicate layer (schematic, not to scale) on the left (Fahn 1964), electron scan microscope picture of a flake-formed sodium-montmorillonite mined in Wyoming on the right (Jasmund & Lagaly 1993).

products are mostly needlepunched, occasionally stitch bonded or adhesive bounded (glued). A special product is the combination of a bentonite mixed with adhesive attached to a thin plastic sheet but in this case the plastic sheet is the dominating sealing element. Needle punched (directional independant) and stitchbonded (directional) GCLs are shear strength transferring (internal shear strength) between the cover and carrier geotextile. GCLs with adhesively bound bentonite transfers shear strength only with the friction angle of sodium-bentonite (3–7°). These GCLs are not suitable for applications on slopes. Geosynthetic clay liners have a permittivity of $1\text{–}5 \cdot 10^{-9}$ 1/sec or a hydraulic conductivity (k) of approximately $1\text{–}5 \cdot 10^{-11}$ m/sec at a thickness of 1 cm. These permittivity- or permeability-values and the swelling volume and water adsorption capacity mentioned above in Table 1 relates to a virgin sodium GCL. If the GCL is installed and covered with soil, an ion-exchange is initiated by calcium-ions in cover-soils leachates.

2 ION EXCHANGE – A CHEMICAL EQUILIBRIUM PROCESS BETWEEN BENTONITE AND PORE SOLUTION

For industrial applications, bentonites are (for the sake of simplicity) divided into sodium bentonites or calcium bentonites, depending on the dominant exchangeable cation. Most of the bentonites used for GCLs have mixed occupations, this means there are (apart from the name-giving main cation which in GCLs is usually sodium), also considerable shares of calcium, magnesium and potassium ions. A typical ion distribution of sodium bentonites used for GCLs could be as follows:

Table 2. Typical ion distribution of commercial sodium bentonites (Egloffstein 1997).

Na^+	Ca^{2+}	Mg^{2+}	K^+	Fe^{2+}	Al^{3+}
50–90%	5–25%	3–15%	0.1–0.8%	<0.5%	<0.5%

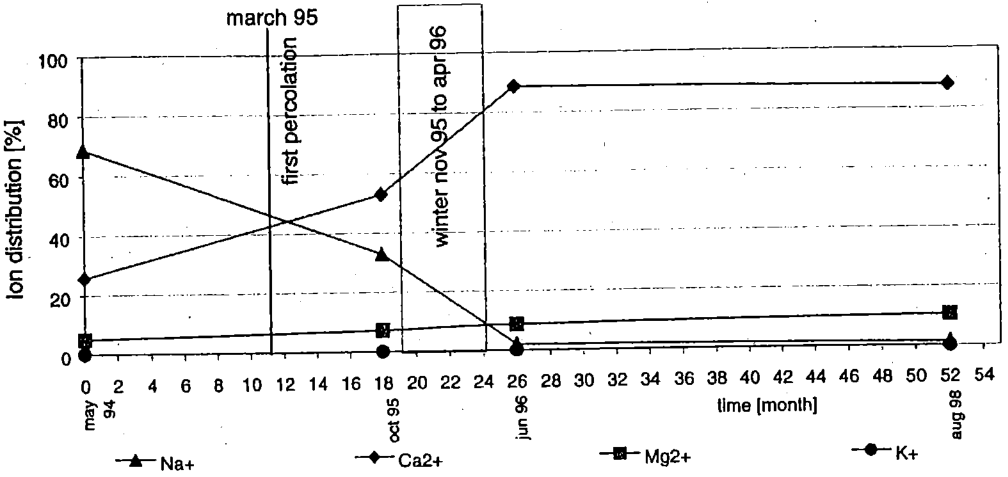

Figure 2. Course of ion exchange over time acc. to excavation results from test fields of the landfill Hamburg-Georgswerder (Egloffstein 2000a).

The clay mineral montmorillonite as the main component of bentonite (>70 MA.%) belongs to the best known natural ion exchangers. In most cases, the naturally occurring bentonites are calcium bentonites, natural sodium bentonites are comparatively rare. In order to receive the better swelling properties of sodium bentonite, calcium bentonite, for instance, is activated with soda (sodium carbonate) and thus the primary calcium ions are exchanged by sodium ions (so-called active bentonite). Ion exchange processes are equilibrium processes. To simplify matters it can be said that the occupation of a cation exchanger depends on the kind and concentration of the cations available for the exchange. Furtheron, the size and, most of all, the charge of the cations are important. For instance, bivalent calcium (Ca^{2+}) is more easily exchanged against monovalent sodium (Na^{+}) than vice versa. In order to activate, for example, a calcium bentonite into a sodium bentonite, high sodium concentrations (excess of soda) are necessary to replace the calcium at the surfaces of the bentonite. On the other hand, calcium concentrations in leachates of soils are likely to exchange 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 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 several years when GCLs are used in partly saturated areas (e.g. landfill cappings).

The duration depends on the primary ion occupation of the bentonite, on the quantity of bentonite per area unit, the geochemical conditions (concentration and ion distribution in the leachate), the geohydraulic conditions (water flow in the GCLs, the quantity of water drained off the GCL) and soil physical conditions (rising ionic concentration in the pore water by reduction of the water content due to desiccation, possibly extension of the contact areas by desiccation cracks).

A GCL retrieved from the test field of the Hamburg-Georgswerder landfill shall serve as an example: This GCL was excavated 3 times over a period of approx. 4 years and the ion occupation was compared to a virgin sample. After approx. 2 years, the natural sodium bentonite of this GCL was completely changed into a calcium bentonite. A change of the ion occupation no longer occurred after two years, as shown in Figure 2.

As shown above, the "in situ" ion exchange of sodium bentonite in GCLs to calcium bentonite is practically always occuring. On one hand, essential calcium (but also a few other ions, e.g. magnesium) is basically outweighing sodium in nearly every kind of soil which is used as a cover for GCLs. On the other hand, the exchange balance between calcium and all other bivalent cations ranges so close to calcium that already small calcium concentrations are sufficient to cause an ion exchange on a long-term basis (Egloffstein 1997).

The 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. The ion exchange of monovalent sodium ions against bivalent calcium or magnesium ions reduces the spaces between the silicate layers (Fig. 3).

The diffuse sodium ion double layer at the surfaces of the clay minerals changes into a central calcium ion layer. The increase of the inner-crystalline attraction by the bivalent ions leads to a certain reduction of volume and a change of the micro structure from smaller, finely distributed clay mineral flakes to larger clay mineral crystals (increase of permeability). At the same time the high water adsorption and swelling capacity of the sodium bentonite reduces to the lower level of a calcium bentonite.

2.1 *Influence of the electrolytic concentration and the ion exchange on micro structure and water permeability*

Sodium bentonites used in GCLs are very finely grained and have a very low water permeability of $k \approx 1\text{–}5 \cdot 10^{-11}$ m/s or respectively a permittivity $\Psi \approx 1\text{–}5 \cdot 10^{-9}$ 1/s. On the electron scan microscope picture of Figure 7, (top left hand side) you see the assembly of montmorillonite flakes or platelets in a pulverized sodium bentonite in a GCL. Seeing this loose, porous structure of montmorillonite flakes the question occurs: Why has bentonite such a low hydraulic conductivity? The answer is: The electron scan microscope picture you have seen was the structure of dry bentonite. In a water saturated bentonite there are some additional effects which cause low hydraulic conductivity.

One of the effects is, that diffuse double layers surround the clay particles (see Fig. 4). These double layers include an ion-distribution with an interaction with the negatively charged surface of the montmorillonite.

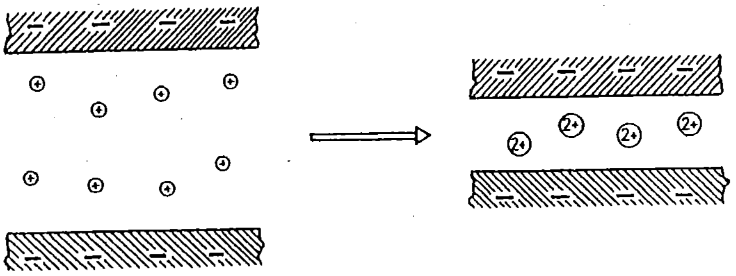

Figure 3. Change from sodium to calcium bentonite (Jasmund & Lagaly 1993).

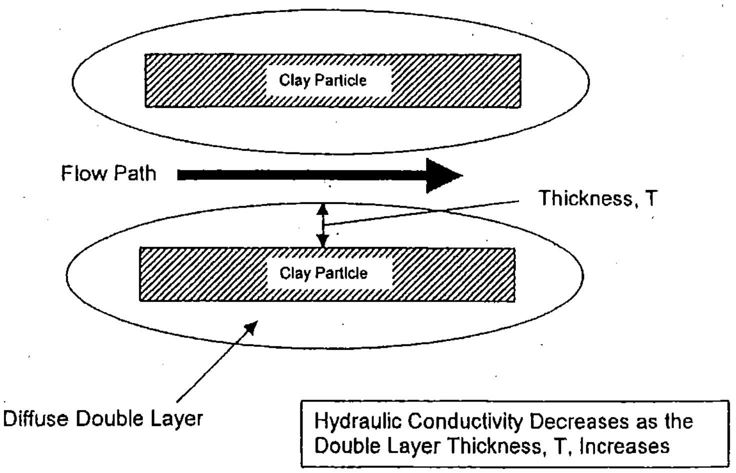

Figure 4. Diffuse double layers surrounding clay particles, blocking flow, and lowering hydraulic conductivity (Daniel 2000).

The thickness of the double layer depends on the electrolytic content of the porous fluid. High electrolytic concentration in the porous fluid decreases the diffuse double layers and increases the hydraulic conductivity.

A second reason for the low permeability are water bindings in the montmorillonite crystal. Only a part of the pore water is free pore water and follows Darcy's law. Adsorption water and hydration water is bound by adhesion stress of the great outer and inner surface of montmorillonite (Fig. 5).

The third reason is the influence of the micro structure.

Due to the partial de-lamination of the silicate layers, sodium bentonites have a smaller average crystal size (colloid clay range) and a more advantageous fine-dispersed micro structure than calcium bentonites (coarser disperse, more aggregate structure, see also Fig. 6 and Fig. 7). This results in a lower flow-efficient pore space with longer flow paths around the individual clay particles. In addition, sodium bentonites form thicker hydrated shells around the clay particles than calcium bentonites due to their higher water binding capacity. This hinders the flow of freely moving pore water through these electrostatically bounded overlapping hydrate shells (Fig. 5).

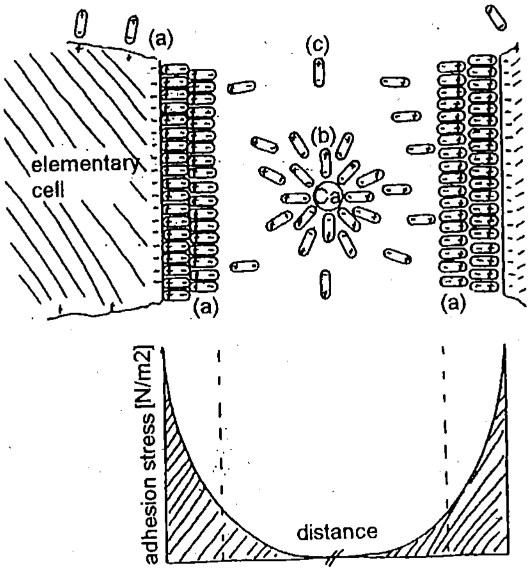

Figure 5. Forms of binding of water in the montmorillonite crystal (Koch 1994). (a) Adsorption water, subjected to high surface tensions (up to 2000 MN/m^2) and is considered to be non-movable, (b) hydration water surrounds the cations with a hydrated shell, is bound by electrostatic forces, (c) free movable pore water.

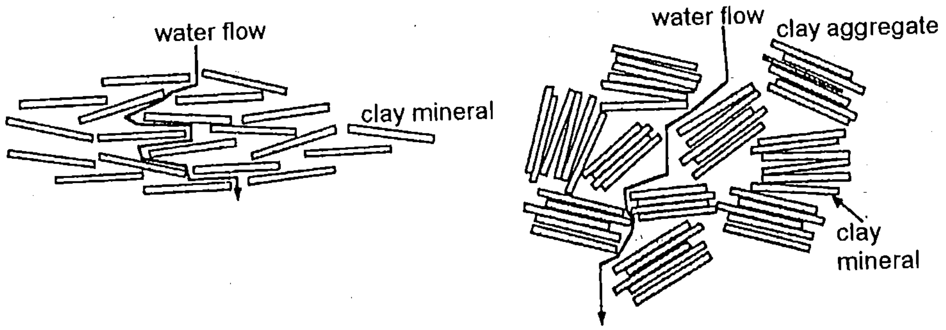

Figure 6. Model conception of the micro structure and the permeability of clay. Left-hand side: dispersed clay, e.g. fine dispersed sodium bentonite. Right-hand side: aggregated clay, such as coarse dispersed calcium bentonite (Hasenpatt 1988).

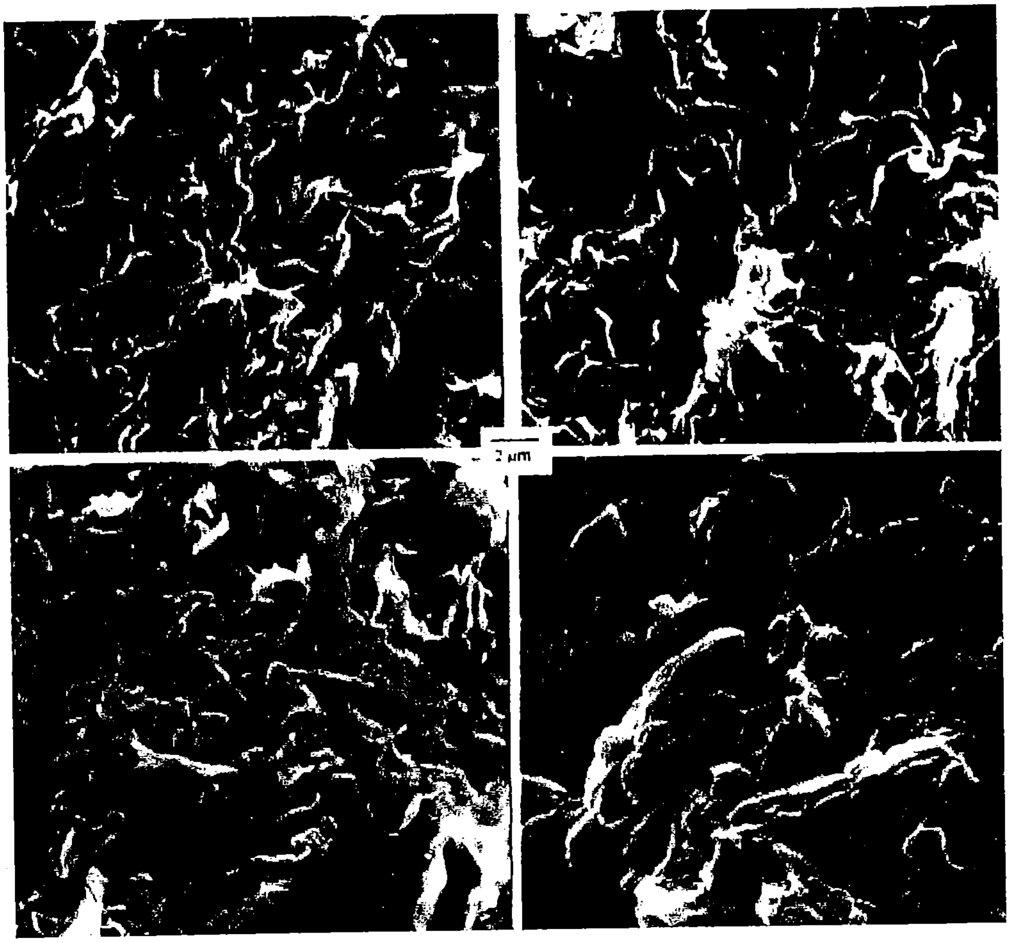

Figure 7. Comparison of the micro structures using electron scan microscope pictures (enlargement = 5000×, 1 cm = 2 µm). *Explanation: Left-hand side, top*: Natural, pulverized sodium bentonite (Wyoming bentonite) with a so-called honeycombed structure. *Left-hand side, bottom*: The same Wyoming bentonite ion-exchanged with 0.3-molar $CaCl_2$ solution. The honeycombed structure is preserved, the montmorillonite flakes, however, are a little bit coarser. *Right-hand side, top*: In-situ ion-exchanged sample (Landfill Hamburg-Georgswerder), excavated after 26 months. The honeycombed structure is preserved to a large extent, however, its shape is a little bit coarser. *Right-hand side, bottom*: Natural calcium bentonite (Calcigel) with coarser montmorillonite aggregates and a coarser structure.

The result of these two effects is an increase of the permeability of primary calcium bentonites by approx. one decimal exponent compared to sodium bentonite.

As a consequence of the ion exchange of a sodium bentonite into a calcium bentonite a certain reduction in volume due to the decreasing distances between the montmorillonite flakes and a loss of water of approx. 6–12% can be observed (Egloffstein 2000a). At the same time, the micro structure is changed from smaller, finely distributed clay mineral flakes to larger clay mineral crystals (see also Fig. 7). This coarser micro structure results in a higher permeability. Laboratory permeability tests carried out by the author, using highly concentrated calcium chloride solutions of 0.3 M $CaCl_2$ (here permeabilitiy is also influenced by the electrolytic concentration; the concentration of the test solution was dictated by other factors, under free choice a test solution of e.g. 0.015 M = solubility of gypsum would have been taken) and the so called ion exchange (sodium against calcium) resulted in an increase of the permeability by approx. 1/3 to 2/3 decimal exponent at a normal tension of 15 kPa compared to the permeability of the original sodium bentonite. Depending on the unit weight, the permeability

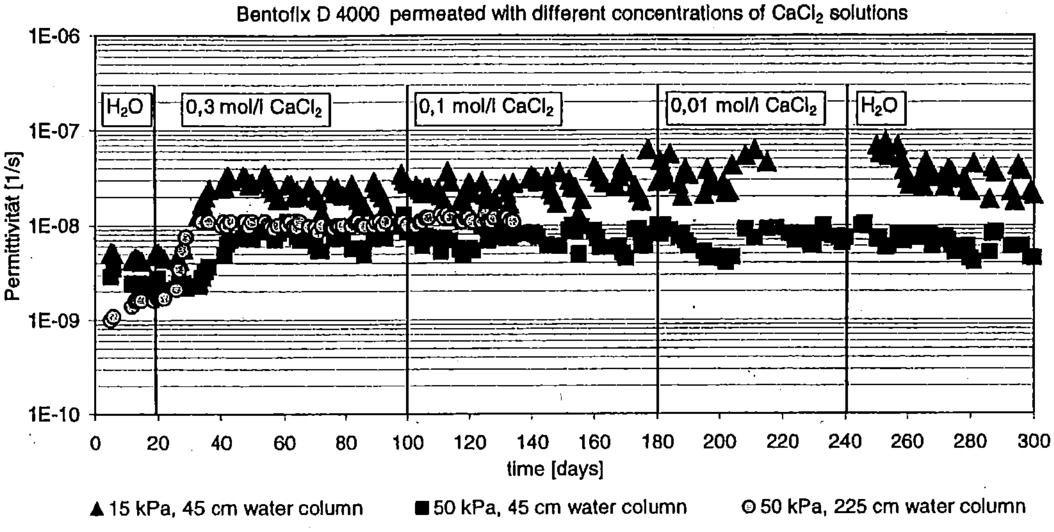

Figure 8. Influence of a 0.3 M $CaCl_2$ test solution on the permittivity of a GCL.

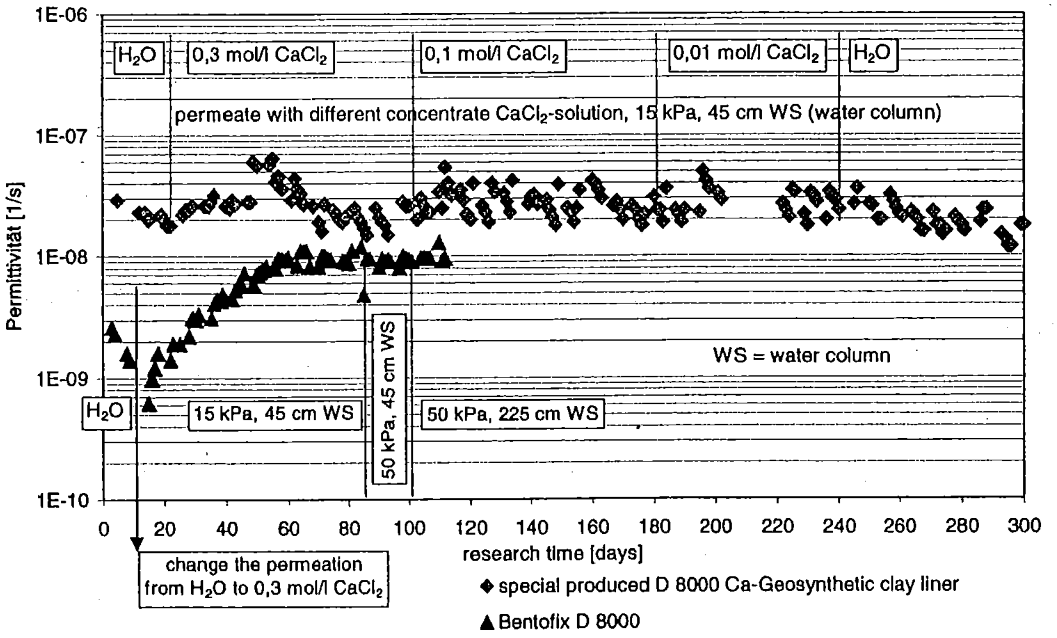

Figure 9. Comparison of the permeabilities of a sodium bentonite GCL and a specially produced GCL using calcium bentonite.

of heavy GCLs (8000 g bentonite/m^2) increases with the average factor 3.1 and of medium-weight GCLs (4700 g bentonite/m^2) with the average factor 6.4. (see Fig. 8).

According to comparative laboratory tests, exchanged sodium bentonites in GCLs have a lower permeability than primary calcium bentonites (see Fig. 9). The direct comparison of the two D 8000 GCLs under identical marginal conditions shows that the sodium GCL had better results (by a factor ≈3) after completion of the ion exchange than the calcium GCL.

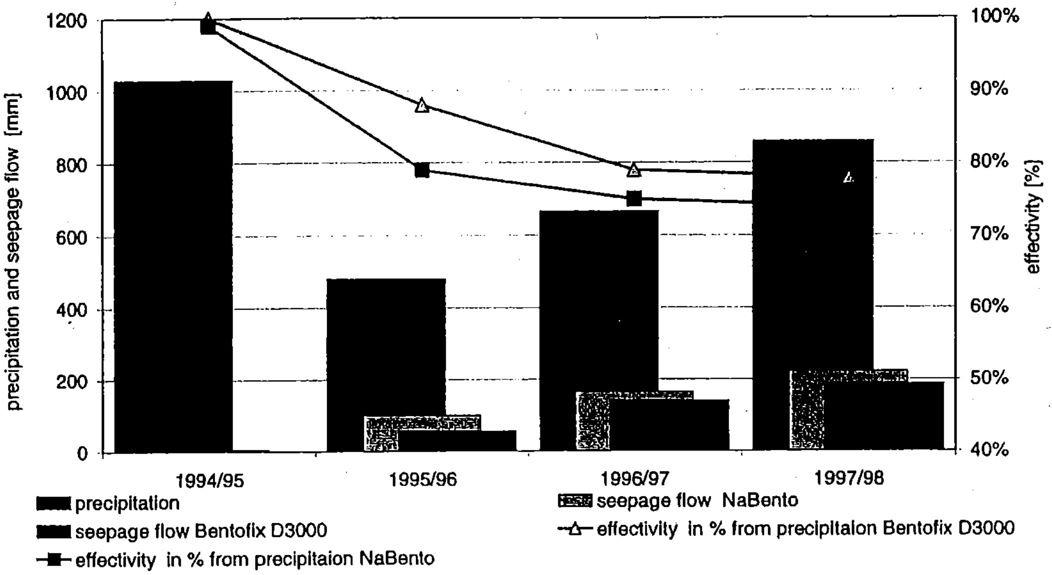

Figure 10. Effectivity of two GCLs from the testplot Hamburg-Georgswerder (results taken from Melchior 1999).

If no further disturbing influencing factors are added (e.g. structural changes due to desiccation) a remaining influence of the originally finer dispersed micro structure of the sodium bentonite seems to be preserved after completion of the ion exchange.

2.2 *Influence of ion exchange with simultaneous partial desiccation*

The influence of ion exchange on the permeability of GCLs (as the only influencing factor) does not explain the considerable increase of seepage flow induced by the increase in permeability, as resolved at the Hamburg-Georgswerder test plots (Fig. 10).

Laboratory tests carried out by Lin & Benson (2000) show a considerable increase of the GCL's permeability from $k \approx 5 \cdot 10^{-11}$ m/s to $k \approx 8 \cdot 10^{-8}$ m/s after flow-through with 0.0125 mol/l calcium and four to six dry-wet series. According to this the influence of the desiccation cracks as a result of the air-drying is much more important, the ion exchange having only an indirect influence. During the first four dry-wet series, the properties of a sodium bentonite with a considerably higher self-healing (swelling) capacity are still prevailing, whereas a change of the properties into those of a calcium bentonite with a clearly lower self-healing (swelling) capacity has to be observed beginning with the fifth series. Under the chosen test conditions (ion-exchanged calcium bentonite, extreme air-drying, 17.5 kN/m^2 normal tension) the calcium bentonite is evidently no longer capable to completely close the desiccation cracks caused by the extreme drying. Only when ion exchange and simultaneous desiccation are combined significant increases of the permeability will result. Therefore, an excessive desiccation of the bentonite has to be avoided by carrying out suitable measures (sufficient covering, water balance control).

According to the author's test results, the significant increase of the permeability after ion exchange and four to six dry-wet series determined by Lin & Benson (2000) has to be attributed to the following facts: On the one hand, the desiccation of the bentonite exceeded the in-situ conditions. On the other hand, the author could measure similar initial permeabilities at excavated GCLs under comparable test conditions (normal tension 15 resp. 20 kPa), however, as time passed, the permeability decreased as a result of the self-healing of the desiccation cracks of the bentonite. Lin & Benson (2000) do not give information on the water contents of the air-dried bentonites. However, it has to be assumed that air-dried bentonite has a water content of approx. 15–20%, depending on the atmospheric humidity. The water contents of the bentonite of approx. twelve GCLs excavated from landfill cappings in Germany (humid climate, precipitation approx. 780 mm/a) usually ranged between 70 and 120%, the lowest water contents ever measured ranging between 40–60% (test-plots Hamburg-Georgswerder).

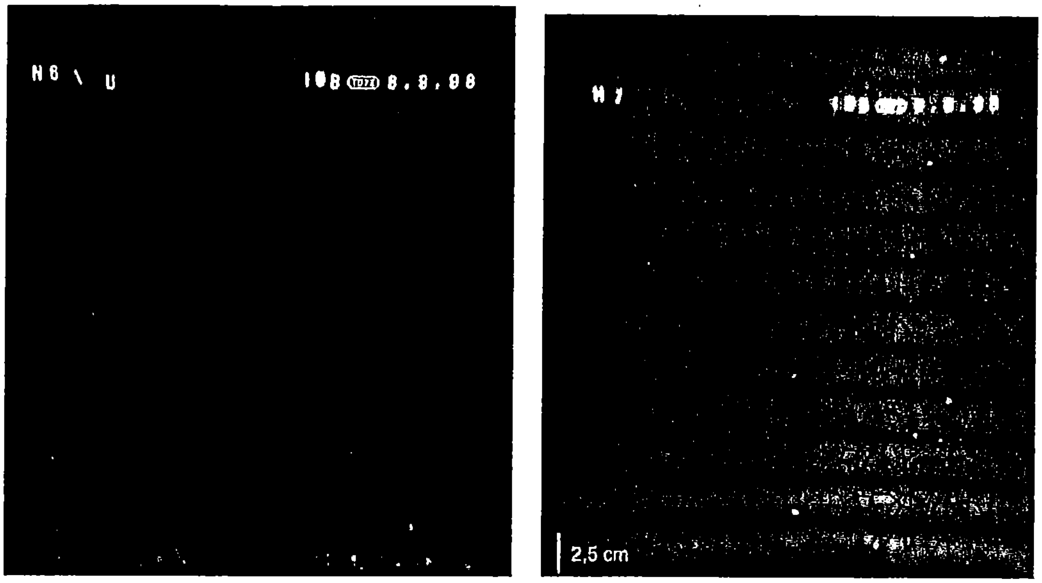

Figure 11. Crack manifestation of a fibre-reinforced GCL and a stitched GCL excavated from the Hamburg-Georgswerder landfill (left picture: fiber-reinforced GCL with 3 kg/m^2 Wyoming-Bentonite, right picture: stitched GCL with 5 kg/m^2 activated bentonite (pictures taken from Melchior 1999).

It has to be stated that according to the author's investigation of excavated ion exchanged and partially dried GCLs (water contents $\geq 52.5 \leq 100\%$), increased initial permeabilities resulting from structural changes in the bentonite layer (beginning to macroscopically visible desiccation cracks) could be found. However, most of these cracks were closed again as a result of the swelling and plastification of the bentonite. This was reflected in a reduction of the permeability by approx. 1 to 2 decimal exponents during the period of testing (see Fig. 12).

As already mentioned above and as it is logically reconstructable, open desiccation cracks in the bentonite have the most influencing effect on GCL permeability. During the period of time which the bentonite requires for water adsorption, swelling and plastification to close the desiccation cracks, an increased water flow through the GCL has to be expected, depending on the extent of the cracking (amount, width and length of cracks) and the hydraulic gradient. The geometry and particularly the width of the cracks in the bentonite layer is decisively dictated by the kind of GCL and especially by its compound. Direct comparisons of excavated GCLs from the Hamburg-Georgswerder landfill (one fibre-reinforced GCL and one stitched GCL) demonstrate this. Whereas the fibre-reinforced GCL shows a tendency of larger quantities of fine desiccation cracks with small crack openings, the stitched GCL has a lower amount of desiccation cracks, which, however, are considerably wider. The crack pattern follows the seams which are arranged at distances of approx. 3 cm. This means, the number of cracks is going up around the seams, the crack openings becoming smaller at the same time in this area. The influence of the fibres and seams on the geometry and width of the cracks in the bentonite layer is thus evident. With respect to the self-healing capacity, which means the closing of the cracks, finer cracks with small crack openings have to be considered to be more advantageous than only a few, but wide cracks.

The result of the ion-exchange without desiccation is a slight increase in hydraulic conductivity (factor 3 to 7) (Egloffstein 2000 a,b). Planning engineers have to consider this when designing low confining stress applications. Results gained from test plots for landfill capping systems in Esch-Belval (Luxemburg), Ansbach und Mengersgreut (Wagner 1999; Henken-Mellies et al. 2001; Siegmund et al. 2001) show an efficacy in relation to rainfall of 98 up to greater than 99% for GCLs. Calculations with the Hydrologic Evaluation of Landfill performance (HELP) model confirm these results (Egloffstein & Markwardt 1999). Understanding that an ion-exchange decreases the excellent swelling capacity of sodium-bentonite the self-sealing capacity of sodium-bentonite is an important factor for the installation. Damages caused during installation are an important issue. They can be self-sealed due to the high swelling of bentonite. Under unsaturated conditions, as typical for low confining stress applications, both sealing elements GCLs and CCLs crack due to desiccation which increases the permeability. This effect occurred for both sealing elements in several test-plots at the landfill

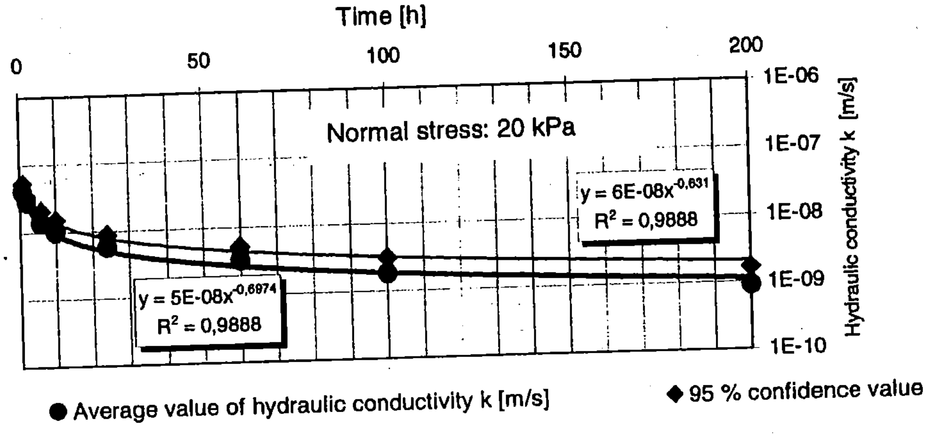

Figure 12. Course of hydraulic conductivity values depend on time. The thick line shows the average values of permeability from 47 excavated samples which was ion-exchanged and partial desiccated. The thin line is the 95% confidence value.

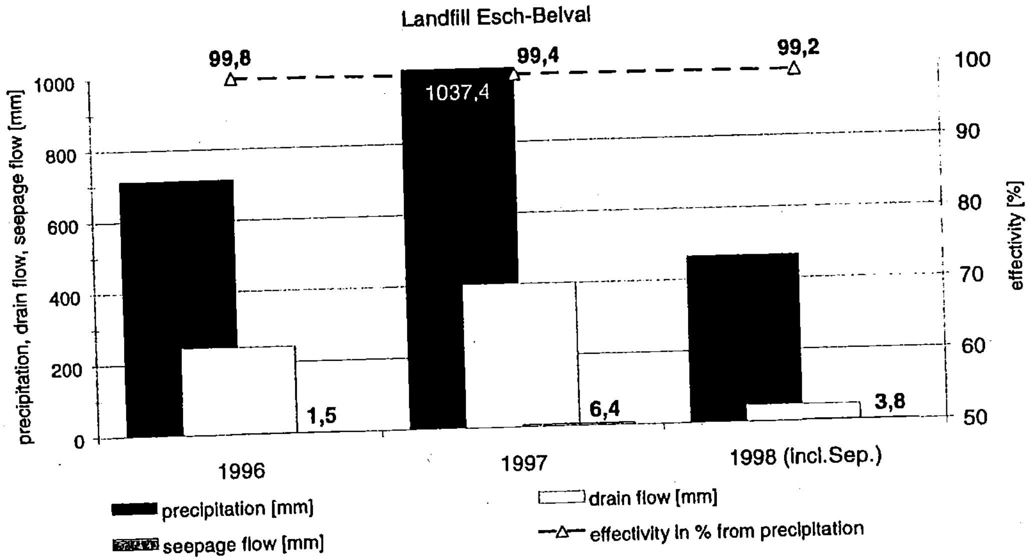

Figure 13. Annual precipitation, drain flow, seepage flow, effectivity in % of Bentofix type B, Landfill EB (results taken from Wagner 1999).

Hamburg-Georgswerder (Melchior 1996, 1999). In contrast to compacted clay liners, where self sealing is not possible under the low confining stress conditions of surface capping systems (Mallwitz & Savides 1996), self-healing/sealing of CCLs takes place by swelling and plastification of bentonite, if soil-cover larger than 0.75 m is provided (Egloffstein 2000a), even after ion-exchange.

3 SUMMARY AND CONCLUSION

Following facts should be noted for the use of CCLs under unsaturated conditions, e.g. landfill capping systems or sealings along highways through water protection areas:

New sodium-Geosynthetic Clay Liners (GCLs) are characterized by:

- very low permeability ($k \approx 1\text{–}5 \cdot 10^{-11}$ m/s)
- virtually perfect self-sealing potential for possible damages during installation

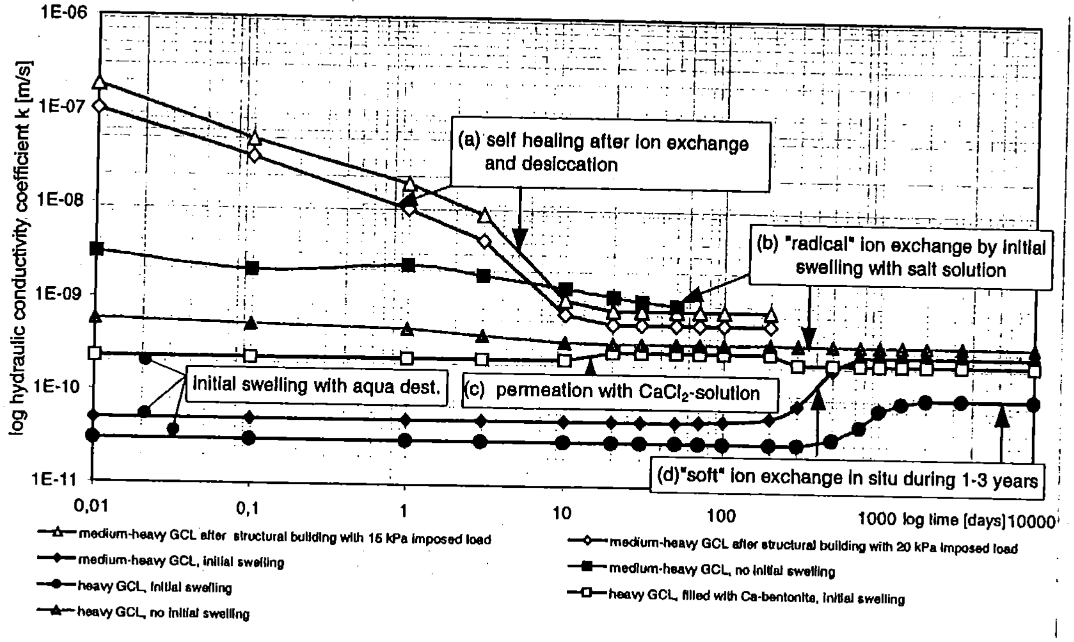

Figure 14. Typical course of permeability for GCLs over the time in dependence of ion exchange, ion exchange and desiccation, self-sealing, electrolytic content, type of bentonite and kind of pre-swelling. The normal stress conditions are 15 to 20 kN/m^2 the hydraulic gradient I = 30–45. *Explanation: Series a*: Course of permeability (self-sealing behaviour) of CGLs after ion exchange and partial desiccation over the time (results from permeability tests with excavated samples). *Series b*: Course of permeability after radical ion exchange by ion exchange by initial swelling with salt solutions (0.3 Mol $CaCl_2$). Note the difference to series d: pre-swelling with de-ionized water before percolation with 0.3 Mol $CaCl_2$-solution. *Curve c*: Course of permeability of a heavy calcium-bentonite GCL (8000 g calcium-bentonite/m^2) after pre-swelling with de-ionized water and percolation with 0.3 Mol $CaCl_2$-solution. The soft increase of permeability (reversible) between 20 and 200 days shows the influence of the high electrolytic content of the 0.3 Mol $CaCl_2$-solution. *Series d*: Course of permeability after soft ion exchange in situ with seepage water of low electrolytic content during 1–3 years. The lower curve shows a heavy GCL with 8000 g sodium-bentonite/m^2, the upper curve a middle heavy GCL with 4000–5000 g sodium-bentonite/m^2. Please note the slight difference in permeability of the primary calcium-bentonite GCL and the ion exchanged calcium-bentonite GCL (≈ factor 3) (see also Fig. 9).

- (swelling volume of bentonite ≈700%)
- >99% effectiveness of the cover system against precipitation (results of several test plots in Germany and help-modellation)

Please note: Several properties of the sodium bentonite in GCLs (e.g. swelling volume, water uptake, permeability) given in many technical bulletins of manufacturer are only valid for the construction phase and a short time afterwards (before ion exchange). With respect to long-term permeability it should be considered permeabilities which are approx. $^1/_2$ to one decimal exponent higher.

A gradual ion exchange in situ (*without desiccation*) causes:

- just a little increase in hydraulic conductivity (factor ≈ 3–7) from $k \approx 1\text{–}5 \cdot 1^{-11}$ m/sec to $k \approx 7\text{–}12 \cdot 10^{-11}$ m/sec. This is not alarming as long as the planning engineers take this effect into consideration.

If ion exchange *and* desiccation occurs under unsaturated conditions (e.g. arid climate, low thickness of cover soil, low water storage capacity of cover soil):

- a significant increase of the *initial* hydraulic conductivity (≈2–3 orders of ten) *can occur*, caused by desiccation cracks

If sufficient normal stress exists (> 15–20 kN/m^2 ≈ 0,75–1 m cover soil, preferably more)

- self-sealing occurs due to intake of water, swelling (swelling volume of dry calcium bentonite ≈ 200%) *an* *plastification* of calcium-bentonite

Please note: To close desiccation cracks in calcium-bentonite GCLs, the plastification of bentonite (t get a softer consistency) *and* sufficient normal stress is necessary among swelling to overpress cracks b load.

If insufficient normal stress exists: (example testplots landfill "Hamburg-Georgswerder": 15 cm drainag layer and 30 cm cover soil ≈9 kN/m^2)

- no self-sealing of calcium-bentonite GCLs can occur
- the sealing element GCL failure due to wrong design

After ion exchange, partial desiccation and self-sealing of desiccation cracks, there is a remaining littl influence of residual crack structures after „self-sealing".

Geosynthetic Clay Liners after ion exchange, partial desiccation and „self-sealing" have:

- a higher hydraulic conductivity than new sodium-GCL's (≈1 order of ten) but:
- the effectiveness against precipitation is sufficient (>95% according to HELP-model, Egloffstein & Markwardt 1999)

Nevertheless, *the best results can be achieved with a desiccation avoiding composition* (even more essential for CCLs without self-sealing under low confining stress conditions).

Precondition for this, is that the GCLs will be covered with a sufficiently thick soil layer which avoid excessive desiccation. On the other hand, the load may be required to close desiccation cracks after repeated watering and plastification of the bentonite. According to tests carried out with excavated GCLs in Germany, a minimum load of 15 kPa, better 20 kPa, is required, this means a cover of approx. 0.75 m, better 1 m of soil and more. To prevent partial desiccation a thick (1,5–2 m) surface layer (cover-soil) with a high water storage capacity should be used for all surface capping systems with GCLs (and CCLs!).

The water balance control using the HELP-model as well as the results from several German test fields show that a 98–99% efficiency of the GCL can be expected after the completion of the ion exchange, if desiccation is prevented.

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