Evaluation of Prototype Geosynthetic Clay Liners
in Landfill Cover Applications

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THESIS
Submitted as partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering in the Graduate College of the University of Illinois at Chicago, 2015

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SUMMARY

Geosynthetic Clay Liners (GCLs) which undergo both wetting and drying cycles in combination with cation exchange (sodium for calcium or magnesium) can experience significant increases in hydraulic conductivity over time. To prevent this from occurring, the current industry standard is to either test the adjacent soil for chemistry to evaluate compatibility (i.e. concentrations of calcium, magnesium, sodium, and other major cations), or to install either a separate overlying geomembrane over the GCL or a geomembrane-laminated GCL. If the soil contains high concentrations of sodium relative to calcium, the GCL can undergo wetting and drying cycles with little or no negative impact on its long-term hydraulic conductivity. If installed with an overlying geomembrane component, the geomembrane would help prevent the bentonite from desiccating, and would therefore also prevent a significant increase in hydraulic conductivity.

The purpose of this project is to investigate prototype GCLs subjected to conditions representative of capping applications. This study exposed prototype polymer-modified bentonite GCLs to several wetting and drying cycles in a calcium-rich solution. After each hydration cycle, samples were allowed to air dry. GCL samples were then tested for hydraulic performance using index test methods and hydraulic conductivity tests, and compared to traditional GCLs that underwent the same conditions. Four separate polymer-modified bentonite (PMB) GCLs were evaluated in this study. PMB-1 demonstrated poor performance after repeated cycles. PMB-2, PMB-3, and PMB-4 demonstrated improved performance, and have the potential to work well as stand-alone barriers in landfill cover applications.
I. INTRODUCTION

1.1 Background

Geosynthetic clay liners (GCLs) typically consist of 3.6 kg/m² of sodium bentonite clay needlepunch reinforced between two geotextiles. The geotextile components are either woven or nonwoven polypropylene based fabrics. In some cases, a geomembrane component can be either laminated or spray-applied to one of the geotextiles. A typical GCL configuration is depicted in Figure 1. The sodium bentonite used for GCLs was created millions of years ago through the deposition of volcanic ash into salt water. The largest deposit of sodium bentonite is available in the United States, primarily in the states of Wyoming and South Dakota. Other deposits around the globe mainly consist of calcium bentonite – which naturally has a much higher hydraulic conductivity. In these regions, calcium bentonite is often converted into sodium bentonite with the addition of soda ash to decrease its hydraulic conductivity.

![Figure 1. Cross-section of a typical needle-punch reinforced GCL](image)

GCLs gained popularity due to their ease of accessibility, installation, and upfront manufacturing quality control testing. In many cases they have a lower overall cost compared to traditional compacted clay liners, especially when the clay hauling distance is significant (Goldenberg, 2012). Due to their low hydraulic conductivity, GCLs are
considered hydraulically equivalent to much thicker compacted clay liners with respect to hydraulic performance. A study conducted for the USEPA (Bonaparte, et. al., 2002) demonstrated that a GCL is at least equivalent to a 0.6 meter thick compacted clay liner with a hydraulic conductivity of $1 \times 10^{-7} \text{ cm/sec}$, in a landfill bottom liner.

Since that time, GCLs have been used in numerous environmental applications - including landfill liners and covers, for containment of coal combustion residuals, in mining applications, as engineered barriers for remediation applications, as hydraulic barriers in many civil engineered applications, and other applications that require the containment of water and/or prevention of contaminants from leaching into the environment. Much has been learned about GCLs over the past several years since they were introduced to the industry. University and industry research has allowed for further standardization of design and installation methods for GCLs. A significant amount of this research has focused on GCLs in cover applications. Unlike base liners, covers are exposed to a variety of environmental stresses, including extreme temperature fluctuations, hydration and desiccation, erosion, root penetration, etc.

1.2 Problem Statement

GCLs have several benefits over prescribed compacted clay liners. However, GCL-only covers have often proved unreliable for long-term hydraulic performance in landfill cover applications. Current standards require either soil compatibility testing or the use of a separate overlying geomembrane (or a geomembrane-backed GCL). Sodium rich soils in the natural environment are rare, and the addition of an overlying geomembrane can add a significant cost to a project. Prototype GCLs have the potential
to perform well in these environments. A test program is needed to validate this hypothesis.

1.3 Purpose of the Study

New polymer-modified bentonite GCLs have the potential to offset the combined effects of desiccation and cation exchange. This study evaluated four polymer-modified bentonite GCLs in conservative conditions for landfill cover environments. Prototype GCLs underwent wetting and drying cycles in a calcium rich solution to mimic worst-case field conditions. After several rounds of wetting and drying, GCL samples were tested for free swell and hydraulic conductivity to assess their hydraulic performance.

1.4 Significance of the Problem

Traditional sodium bentonite-based GCLs have experienced decreased performance over time in certain landfill cover installations. Research has demonstrated that sodium bentonite which undergoes desiccation adjacent to calcium or magnesium rich soils can convert to calcium or magnesium bentonite, and in turn see a significant increase in hydraulic conductivity. This results in a hydraulic barrier that is several orders of magnitude higher in hydraulic conductivity compared to the new material. This higher hydraulic conductivity allows rainwater to percolate into the landfill, and create unexpected increases in leachate generation.

1.5 Significance of the Study

Past research on polymer-modified GCLs has focused on bottom liner performance with aggressive leachates (Scalia and Benson, 2011; Athanassopoulos and
Benson, 2015; Benson, Chen, Edil, 2014). This study is one of the first to evaluate prototype polymer-modified GCLs in conditions that are representative of landfill covers. If the GCLs demonstrate acceptable hydraulic performance after being subjected to the conditions in the testing, this may be a first step toward using these materials in landfill cover applications.

This report will provide a historical background on GCLs in cover applications, the reasons for the impacted performance in some of the cases studied, current recommendations for GCLs in cover applications, and the results of a testing program with prototype GCLs in laboratory conditions representative of aggressive conditions for a landfill cover environment.
II. BENTONITE PROPERTIES AND BEHAVIOR

2.1 Bentonite Mineralogy

Bentonite in GCLs is sensitive to chemical interactions with the surrounding environment. The liquid that comes in contact with the bentonite and the surrounding porewater chemistry in the soil can both affect bentonite’s long-term performance (Shan and Daniel 1991, Petrov and Rowe 1997, Shackelford et al. 2000). The sodium in the bentonite is able to exchange with other cations that the bentonite comes in contact with. Valence size, ion size, and the relative abundance of the cations in solutions and on the clay surface all factor into the likelihood of exchange occurring (Grim 1968, Mitchell 1993). Cations of higher valence and smaller particle size tend to replace cations of lower valence and larger size. According to Mitchell (1993) and McBride (1994), the following series is representative of exchange preference: $\text{Na}^+ < \text{Li}^+ < \text{K}^+ < \text{Rb}^+ < \text{Cs}^+ < \text{Mg}^{2+} < \text{Ca}^{2+} < \text{Ba}^{2+} < \text{Cu}^{2+} < \text{Al}^{3+} < \text{Fe}^{3+} < \text{Th}^{4+}$. Cations most likely to be replaced are towards the left. For instance, when sodium bentonite is permeated with a solution containing calcium, the sodium will typically be replaced by calcium. This replacement series is applicable when the concentrations of the cations are comparable. If a cation on the left (lower preference) has a concentration that greatly exceeds a cation of greater preference, the lower preference cation may still replace the higher preference cation. The types of cations that occupy the exchange complex can greatly influence that the structure of montmorillonite as it hydrates.

The primary mineral in bentonite is montmorillonite, a member of the smectite group. Montmorillonite has a 2:1 crystalline structure where two silica tetrahedral sheets surround a central alumina octahedral sheet (Grim 1968). Mitchell (1993) documented
that substitution in the octahedral sheet may be very limited or nearly complete. Within the octahedral sheet, the aluminum atoms can be replaced by magnesium, iron, zinc, lithium, or other metals. Grim (1968) documented that total substitution of the central atom in the tetrahedral sheet is limited to approximately 15%.

Figure 2. Montmorillonite Structure (Courtesy of Craig Benson, UW Madison)

Two types of swell can occur during bentonite hydration – crystalline and osmotic (Norrish and Quirk 1954). During the crystalline phase, water molecules move into the interlayer space and hydrate the mineral surface. The crystalline phase forces the crystal layers to separate from approximately 0.3 nm (dry) to 2 nm when hydrated. The osmotic phase follows, but only when monovalent cations occupy the interlayer space (Norrish and Quirk 1954, McBride 1994). This is a function of the electrostatic attractive force between the hydrated cations and the clay layers. When polyvalent cations are dominant, the force is strong enough to balance the repulsive force that develops due to osmosis, preventing osmotic swell. However, when monovalent cations are present, the attractive
force between the hydrated cations and the clay layers is not strong enough to prevent osmotic expansion, allowing a much greater swell.

Figure 3. Osmotic and Crystalline Swell vs Pore Water Cations (Courtesy of Craig Benson, UW Madison)

The water molecules that enter the interlayer space and hydrate the cations are electrostatically bound to the clay surface along with the cations. This bound water is immobile and further reduces the pore space through which water can flow. This in turn decreases the hydraulic conductivity of bentonite and creates a more tortuous flow pathway (McNeal and Coleman 1966, Mesri and Olson 1971). Montmorillonite that undergoes both crystalline and osmotic swelling experiences more swell and lower hydraulic conductivity, as compared to montmorillonite that only undergoes crystalline swell.
Calcium bentonite is far more common around the globe than naturally occurring sodium bentonite. For this reason, calcium bentonite is often activated using soda ash to convert it into the significantly less permeable sodium bentonite. The typical ion distribution of sodium bentonite is as follows (Egloffstein, 2000):

\[
\begin{align*}
\text{Na}^+ & \quad 50 – 90 \% \\
\text{K}^+ & \quad 0.1 – 0.8 \% \\
\text{Ca}^{2+} & \quad 5 – 25 \% \\
\text{Fe}^{2+} & \quad < 0.5 \% \\
\text{Mg}^{2+} & \quad 3 – 15 \% \\
\text{Al}^{3+} & \quad < 0.5 \%
\end{align*}
\]

Divalent calcium is more easily exchanged against the monovalent sodium, as compared to the opposite. For this reason, to activate calcium to sodium, much more sodium would be necessary. In contrast, much smaller concentrations of calcium would be necessary to exchange sodium bentonite to calcium bentonite. As sodium is exchanged for calcium or magnesium, the space between the silicate layers decreases. The diffuse sodium ion double layer is converted into a central calcium ion layer, which results in larger clay mineral crystals, and an increased hydraulic conductivity. This further reduces the swell and water adsorption capacity of the bentonite (Egloffstein, 2000).

![Figure 4. Bentonite Platelet Swell (Image from Jasmund and Lagaly, 1993)](image)

Ion exchange is reported to take place over a one to three year period. In a hydrated system, the exchange of sodium for calcium can lead to a modest increase in
hydraulic conductivity of approximately a half order of magnitude. In landfill caps however, the exchange process often occurs in conjunction with drying. As a result, desiccation cracks tend to form, and because of the reduced swell potential of calcium bentonite, these cracks do not fully heal, leading to much larger increases in hydraulic conductivity. Sufficient confining pressure can limit the increase in hydraulic conductivity (Rowe, 2013).

2.2 Bentonite Free Swell and Hydraulic Conductivity

Sodium bentonites behave very differently from calcium bentonite. For instance, when in contact with deionized water (DI), the free swell of sodium bentonite is approximately 30 mL/2g. Calcium bentonite may only swell 5 to 10 mL/2g (Egloffstein 1995, Lin and Benson 2000, Kolstad 2000, Jo et al. 2001). As a result, sodium bentonite’s hydraulic conductivity values can range between $6.0 \times 10^{-10}$ cm/sec and $1.5 \times 10^{-9}$ cm/sec with DI water (Petrov and Rowe 1997, Gleason et al. 1997, Shackelford et al. 2000, Kolstad 2000, Jo et al. 2001). In comparison, calcium bentonite may have hydraulic conductivity values on the order of $10^{-6}$ or $10^{-5}$ cm/sec. Because sodium bentonite is limited in its availability around the globe, and is considered rare compared to calcium bentonite, calcium bentonite is frequently activated using soda ash and converted into sodium bentonite.

There are two primary factors that affect the free swell and hydraulic conductivity of bentonite - the valence of cations and the ionic strength of the hydrating liquid (Ruhl and Daniel 1997, Petrov and Rowe 1997, Shackelford et al. 2000, Kolstad 2000, Jo et al. 2001). When the hydrating liquid contains high ionic strength or is predominantly divalent, the amount of expansion in the interlayer space is reduced, and the fraction of mobile water increases in the void space (Mesri and Olson 1971). These conditions result in
decreased free swell and increased hydraulic conductivity (Petrov and Rowe 1997, Shackelford et al. 2000, Kolstad 2000, Jo et al. 2001). Joe et al. (2001) demonstrated the effect on bentonite free swell and hydraulic conductivity when in contact with solutions consisting of 0.1 M and 1.0 M NaCl. The hydraulic conductivity was 4 orders of magnitude lower and the free swell was 25 mL/2g higher with the lower strength solution. These results are consistent with Petrov and Rowe (1997) and Kolstad (2000).

2.3 Significance of Bentonite Chemical and Mechanical Behavior in Landfill Covers

Calcium and magnesium are the predominant cations typically found in natural soils (Sposito 1981). As noted above, the exchange of calcium or magnesium for sodium is thermodynamically favorable. The most likely source of calcium and magnesium is percolation from the overlying soil. Although upward diffusion from the underlying soil may also be a factor in the ion exchange process. Unless there is an abundance of sodium as compared to calcium, exchange within the bentonite will likely result.

However, cation exchange in itself will typically not result in a significant increase in hydraulic conductivity of a GCL. As described in detail in the following sections, bentonite subjected to both cation exchange and desiccation can see an increase in hydraulic conductivity by several orders of magnitude. Desiccation or cation exchange on their own are unlikely to cause these increases. A landfill cover, depending on the geographic location, can see dry conditions for extended periods of time, which can result in GCL desiccation.
III. LITERATURE REVIEW AND EXPERIMENTAL BACKGROUND

3.1 Shan and Daniel (1991) – Results of Laboratory Tests on a Geotextile/Bentonite Liner Material

To demonstrate that desiccation on its own does not affect bentonite’s long-term hydraulic performance, Shan and Daniel subjected GCL specimens to wetting and drying cycles with clean water. As the sample desiccated, cracks as wide as 2 mm were observed. Upon permeation, the hydraulic conductivity was on the order of $1 \times 10^{-6}$ cm/sec. After a few hours, the bentonite hydrated and the hydraulic conductivity decreased back to low levels. The bentonite self-sealed when re-hydrated. Specimens were subjected to three cycles, with a low hydraulic conductivity through each cycle upon bentonite hydration. The authors concluded that wetting and drying cycles, at least with tap water, did not result in increased GCL hydraulic conductivity.

3.2 Boardman and Daniel (1997) – Hydraulic Conductivity of Desiccated Geosynthetic Clay Liners

Boardman and Daniel tested three commercially available GCLs, each with different geotextiles and/or reinforcement mechanism. All three contained similar sodium bentonite clay. Clean water was used as the permeant liquid. Large scale testing was performed in rectangular steel tanks measuring 2.4 m in length, 1.2 m in width, and 0.9 m in depth were used. A 12 mm diameter drainage port at the center of the base of each tank provided an outlet for drainage, as water passed through the GCL. Intact and overlapped samples were installed. Overlapping samples were installed with bentonite between the seams, as recommended by the manufacturers. One of the specimen was
a geomembrane-backed GCL, which was tested with an overlap. The GCL was attached to the frame. 24 mm diameter polyvinyl chloride (PVC) piezometer was placed above the GCL in the center of the tank to determine the water level in the gravel that would cover the GCL. Eight PVC pipes were installed above the GCL vertically. Six of the pipes were used to inject hot air and two were used to extract air from the gravel over the GCL. As the GCL permeated, 300 mm of water head was applied to the GCL. It took between 2 and 3 weeks for the GCL to dry.

The geotextile-backed products initially experienced an increased hydraulic conductivity. However, upon bentonite rehydration, the long-term hydraulic conductivity decreased to $10^{-9}$ cm/s levels. The geomembrane backed GCL maintained a consistently low hydraulic conductivity. It was also noted that the increase in hydraulic conductivity after desiccation may not be representative of field conditions, because soil and not gravel are typically installed over a GCL. Soil would more slowly adsorb water, and allow the GCL to hydrate more gradually prior to significant permeation with water.

3.3 Melchior (1997)

Melchior (1997) studied the performance of compacted clay and GCLs in landfill cover systems. Rather than mimicking the field conditions representative of landfill covers in a lab, in-situ test plots were constructed containing compacted soil liners, GCLs, capillary barriers, and composite liners which included geomembranes overlying compacted soil liners in a landfill. Six field plots were integrated into a landfill cover in Hamburg, Germany to study the water balance and liner performance. Field plots were monitored for eight years. The study found that the compacted soil liner, the GCL, and the capillary barrier systems performed well initially, but eventually increased in
permeability, with high leakage rates as a result. Compacted soil liners desiccated, which created flow paths for water to pass through. In one test plot, the leakage during the first year was as low as 1.9 mm, and eventually increased to as high as 150 mm for the last year of the study. The capillary system also performed poorly after the compacted soil above the capillary system desiccated, and the lateral drainage capacity of the capillary layer was exceeded. In both systems, plant roots had penetrated the system, which also may have contributed to increased leakage rates.

The GCL performed well during the first year. However, after a dry summer the overlying cover soil, and the adjacent GCL desiccated. Thereafter, the leakage rates through the GCLs were high during each major rainfall event. The data suggested that calcium ions had exchanged for sodium ions, which resulted in the GCL consisting of calcium bentonite with less swell capacity and greater hydraulic conductivity. Root penetrations were also evident through the GCL systems. It should be noted that multiple GCL samples from different manufacturers were used for this study, with consistent results regardless of the product. All GCLs tested were bentonite encased between two geotextiles.

3.4 Melchior (2002)

In the years following the initial field study by Melchior, several GCL samples were excavated and evaluated for physical and chemical changes to the samples. X-ray images of the excavated GCL samples demonstrated significant cracks within the bentonite layer of the excavated samples. The geomembrane-backed GCL was an exception to this, as it had remained hydrated.
Cation exchange capacity (CEC) and the montmorillonite content (which was determined using VDG P69 method, a methylene blue test) did not change significantly since the GCLs were installed in the test plots. However, while the CEC remained consistent, the cation fractions absorbed on the negatively charged areas of the clay did have significant changes (again the geomembrane-backed sample was the exception). For instance, when the samples were originally installed, the sodium content contributed between 61 percent and 90 percent to the total of absorbed sodium, potassium, magnesium, and calcium. Four years later (in 1998), the sodium contributed between two and four percent for the geotextile-encased samples. The geomembrane-backed sample still had a high proportion, approximately 55 percent. During the same time period, the calcium contents increased from 7 percent and 26 percent to 81 and 83 percent, effectively converting the sodium bentonite into calcium bentonite in the geotextile-encased products. In the geomembrane-backed GCL, the calcium content increased from 20 to just 28% in the same time frame.

Due to these chemical composition changes, performance changed accordingly. Bentonite swell decreased from 25 and 30 mL/2g to 8 and 15 mL/2g. Water absorption over a 24 hour period changed from 410 and 600 percent to 150 and 250 percent. Again, the geotextile-encased GCLs experienced these major changes in both instances. The geomembrane-backed sample decreased in performance as well, but not to the same extent. Swell for this sample decreased from 20 mL/2g to 12 mL/2g, and water absorption decreased from 690 to 490 percent.
3.5 Lin and Benson (2000)

Following the initial 1997 report by Melchior, Lin and Benson initiated laboratory testing to evaluate how wet-dry cycles in contact with different waters would affect the performance of bentonite. Three different liquids were used in this study, including deionized (DI) water, tap water, and 0.0125-M CaCl$_2$ solution – which was based on the pore water extracts from natural vegetated soils in Wisconsin.

The tap water had a measured electrical conductivity (EC) of 0.0005 mS/cm, which was used as the control. The tap water had a measured EC of 0.59 mS/cm and the 0.0125 M calcium chloride solution had measured EC of 2 mS/cm. The CaCl$_2$ solution was selected to represent the predominance of divalent cations, including calcium (Ca$^{2+}$) and magnesium (Mg$^{2+}$). The pH of the solutions were near neutral, between 6.2 for the calcium chloride solution and 6.8 for the tap water. The DI water had a pH of 6.5.

Atterberg limits, swell tests, and hydraulic conductivity tests were performed on the initial specimens and after each cycle. When in contact with DI water, the liquid limit and plasticity index increased with each cycle. The reason for this is that some of the Na$^+$ ions are washed out during each cycle, and the result is an increase in the double layer thickness, resulting in a more plastic bentonite. When in contact with the tap water and the calcium chloride solution, the liquid limit and plastic index decreased after each wetting and drying cycle. The tap water contained high quantities of calcium and magnesium, among other ions of lower concentration (potassium, sodium, and copper). The divalent cations replaced the sodium, which resulted in a decreased double-layer thickness and plasticity. Regardless of the decrease in liquid limit (LL) and plasticity index (PI), these values were still much greater than those reported for calcium bentonite. The
lowest liquid limit and plasticity index were approximately 300 (with the calcium chloride solution). Historic testing by Gleason et al. (1997) reported LL and PI of 124 and 98 for calcium bentonite. Accordingly, as the number of wet dry cycles increases, the LL and PI of the sodium bentonite should further decrease.

Swell with DI and Tap water remained relatively constant through seven cycles, with values of 35 mm and 40 mm, respectively. When in contact with the calcium chloride solution, the swell decreased drastically. After just three cycles, the swell decreased from 20 mm to approximately 8 mm. After seven cycles with the calcium chloride solution, the swell measured just 4 mm. Samples were also initially hydrated with DI and tap water, prior to hydration with the calcium chloride solution. Some delay of reduction in swell was observed; however, in both cases the bentonite swell decreased to levels close to that of initial hydration with calcium chloride solution.

Hydraulic conductivity tests were consistently low through five cycles with DI water. When permeated with calcium chloride solution, the rate remained low through three cycles, then increased rapidly by several orders of magnitude to $7.6 \times 10^{-6}$ cm/sec after six cycles. The end result was similar when initially hydrated with DI water and calcium chloride subsequently, only delayed by a couple of cycles. Hence, initial prehydration with clean water in conditions where wet-dry cycles with calcium or magnesium solution is expected will not deter an ultimately increased hydraulic conductivity value. Dye tests demonstrated that preferential flow rates occurred through cracks in the GCL that did not fully heal after repeated wetting and drying when in contact with the calcium chloride solution. These results were consistent with the measured thickness of the GCL after
each cycle. The thickness increased after each cycle with DI water; whereas the thickness of the GCL decreased after the third cycle with the calcium chloride solution.

3.6 Mackey and Olsta (2004) – Performance of Geosynthetic Clay Liners used in two Landfill Closures in a Coastal Area of Florida

Mackey and Olsta evaluated installed GCLs in two landfill closures in a coastal area of Florida (Landfill sites “Alpha” and “Beta”). Florida’s predominant soil type is sand overlaying former shell and coral deposits. These deposits are known to have high calcium contents. A woven-nonwoven geotextile-encased GCL was used as the hydraulic barrier in these landfills. The manufacturer’s test data on the GCL at the time of initial quality control testing showed sufficient bentonite content, proper swell (24 mL/2g), a low fluid loss (15 mL), and a low hydraulic conductivity 9.5x10^{-10} cm/sec to 4.1x10^{-10} cm/sec under 13.8 kPa (2 psi) confining pressure.

Cover soil depths ranged from 0.46 m to 0.86 m at one landfill, and 0.61 m to 0.81 m in the other. Exhumed samples were tested by the manufacturer, as well as an outside testing laboratory. Plant roots were noticeable on the nonwoven geotextile (the geotextile facing down against the subgrade); however, it was not evident that the roots had penetrated the GCL. Upon testing, the manufacturer recorded hydraulic conductivities ranging from 8.5 x 10^{-9} cm/sec to 2.1 x 10^{-8} cm/sec at Landfill Alpha. The outside testing lab however measured higher hydraulic conductivities, between 1.2 x 10^{-7} cm/sec and 6.4 x 10^{-6} cm/sec. The swell index was between 8 and 8.5 mL/2g. The hydraulic conductivities at Landfill Beta ranged from 4.8 x 10^{-9} cm/sec to 2.3 x 10^{-8} cm/sec, and were in agreement between the outside lab and the manufacturer. The swell index measured lower values, and the fluid loss measured increased values from the original test values. X-ray
diffraction on the exhumed samples showed that a very small percent of sodium was still available in the bentonite (0.04 to 0.09%). A higher percent of calcium was present however (1.41 to 3.40%). Landfill Alpha had approximately twice as much calcium in the GCL as compared to Landfill Beta, which is consistent with the lower hydraulic conductivity in Landfill Beta. The cover and subgrade soils in Landfill Alpha contained sodium contents between 0.01% and 0.03%, while the calcium contents ranged between 6.41% and 15.51%. This paper also noted the potential benefit of higher confining pressure. As the confining stress increases, the hydraulic conductivity tends to decrease.

3.7 Albright et al. (2004)

As part of the Alternative Cover Assessment Program (ACAP), alternative covers consisting of geomembrane overlying GCLs were deployed to assess their performance over time. Two sites in particular included composite covers with a GCL in place of compacted clay – Apple Valley, California and Boardman, Oregon. Apple Valley receives 112 mm of precipitation annually, and is considered arid. Boardman receives 215 mm of precipitation annually and is considered to be semi-arid.

The California installation included 300 mm of sand installed above the geomembrane, which covered the GCL. 5 years after installation, the GCL installed in California was uncovered and samples were taken. Roots or desiccation cracks were not evident. The hydraulic conductivity values of the GCL samples taken ranged between $1 \times 10^{-9}$ and $3 \times 10^{-9}$ cm/sec. Despite the low hydraulic conductivity values, low concentrations of sodium remained within the GCL – only 23%. Much of the sodium was replaced by calcium and magnesium. This was confirmed by the swell of the bentonite, which ranged between 13 and 16.5 ml/2g. Based on this, cation exchange had still
occurred within the GCL, despite the presence of an overlying geomembrane. Because the GCL maintained a high moisture content, cation exchange had not resulted in increased hydraulic conductivity.

In Boardman, Oregon, the cover consisted of 900 mm of silt, geocomposite drainage layer, textured HDPE geomembrane, GCL, and 300 mm of silt beneath the GCL. No percolation was recorded over a 4 year monitoring period. After 6.7 years, GCL samples were collected. Roots were not present; however, the bentonite still appeared to be granular, i.e., it did not fully hydrate. The subgrade was dry as well, which likely limited the amount of water the GCL had access to for hydration. Still, a significant amount of sodium was replaced by calcium and magnesium, which resulted in a lower fee swell, between 16 and 17 mL/2g. The exchange likely occurred from upward migration of divalent cations from the subgrade. Hydraulic conductivity values ranged between $1.3 \times 10^{-9}$ and $2.3 \times 10^{-9}$ cm/sec with DI water. When permeated with a 0.01 M CaCl$_2$ solution, the values increased to between $8.5 \times 10^{-8}$ and $1.9 \times 10^{-6}$ cm/sec. The explanation for the wide difference in values is that the bentonite was transitioning with respect to cation exchange. Full exchange was not yet realized.

It was concluded that GCLs that hydrate and undergo cation exchange, and maintain their hydration, will maintain low hydraulic conductivity values. GCLs that hydrate, undergo cation exchange, and dehydrate or never fully hydrate to begin with can see significant increases in hydraulic conductivity. To offset these effects, Scalia and Benson (2012) recommended that GCLs should be installed under conditions that promote rapid hydration and prevent desiccation. GCLs should be placed on subgrades prepared at optimum or wet of optimum moisture content.
Test plots were constructed on a final cover for a coal ash landfill in southwestern Wisconsin. The site receives of 892 mm of precipitation annually. A conventional (geotextile-encased) GCL was installed in 1996 during the completion of the final cover construction. A 760 mm thick vegetated surface layer consisting of silty sand was installed over the GCL. Silty sand was installed beneath the GCL, as this was used as an interim cover soil over the ash. Lysimeters were installed beneath the cover to monitor the percolation rate. During the first month of installation, the measured percolation rates were low (<13 mm/year). Over the next 4-7 months, the percolation rates increased to as much as 299 mm/year, much higher than expected since a GCL with a typical hydraulic conductivity of $2 \times 10^{-9}$ cm/sec would be expected to allow less than 1 mm of percolation per year. Accordingly, it was reasonable to assume that the GCL’s performance had changed in a relatively short time period.

Initial concern was that gravel particles in the lysimeter potentially caused stress concentrations in the GCL, making it thinner and more permeable. Due to this concern, the cover was removed in each location with the lysimeter, sand was placed on top of the gravel, a new GCL was installed with the same cover profile installed. Percolation rates remained low for 9-15 months after reconstruction, but increased again to 450 mm/year. The second lysimeter was rebuilt again after 24 months, and this time a composite GCL (consisting of a geofilm component installed downward) was installed in place of the conventional GCL. The first lysimeter was also reconstructed 49 months after the first using the same composite GCL, but this time with the geofilm installed upward. Average
percolation rates were 2.6 mm/year and 4.1 mm/year, for lysimeters one and two, after 28 and 65 months, respectively.

![Figure 5. Standard and composite GCL test results from Benson et al. (2007)](image)

The original GCL samples were exhumed for testing. The findings in the field showed that the GCL overlaps were intact without construction defects. Bentonite from each sample was removed and tested for water content, swell index, and abundance of exchangeable ions (Na, K, Ca, and Mg). Cation exchange capacity was determined for the new GCL. Hydraulic conductivity tests were also performed on the new and exhumed GCL specimens. Three liquids were used as the permeant – DI water, 0.01 M CaCl₂ solution, and synthetic percolate. The synthetic percolate was created with collected effluent from a hydraulic conductivity test on an undisturbed block sample from the overlying cover soil. The solution had an ionic strength of 0.0089 M and an RMD of 0.0033 M^{1/2}. The RMD is the ratio of monovalent to divalent cations in solution, or \( RMD = \frac{M_M}{\sqrt{M_D}} \).
where \( M_M \) = total molarity of monovalent cations, and \( M_D \) = total molarity of divalent cations in the solution.

The new GCL contained 55.2 cmol\(^+\) of sodium and 2.2 cmol\(^+\) of calcium. The exhumed samples contained less than 2 cmol\(^+\) sodium and between 21.3 and 26.4 cmol\(^+\) calcium. Clearly ion exchange had occurred in the GCL samples tested. As expected, the new GCL sample measured a swell index of 24 mL/2g. The hydraulic conductivity values for the new specimen were in the \( 10^{-9} \) cm/sec range for all three solutions, with the rainwater percolate being the highest with a value of 7.8x\( 10^{-9} \) cm/sec. The original non-composite exhumed samples measured hydraulic conductivities between 1.7x\( 10^{-8} \) and 1.6x\( 10^{-5} \) cm/sec with the 0.01 CaCl\(_2\) solution, between 1.0x\( 10^{-8} \) and 2.3x\( 10^{-5} \) cm/sec with the rainwater, and between 8.5x\( 10^{-8} \) and 3.6x\( 10^{-5} \) cm/sec with DI water. These hydraulic conductivities were more than three and in some cases nearly four orders of magnitude higher than those for the new GCL.

Osmotic swelling occurs when monovalent cations are the predominant cations in the hydration liquid. As mentioned earlier, osmotic swell does not occur with polyvalent cations are dominant. The hydraulic conductivity of bentonite is both a function of the hydration liquid and the strength of the solution that the bentonite would be in contact with. In large part, the performance of bentonite is dependent on the availability of compatible solution. For instance, when a GCL is permeated with a dilute salt solution (<20 mM), hydration is nearly complete after about 1-3 pore volumes, while complete ion exchange may not occur until after hundreds of pore volumes of flow. However, if permeated with a concentrated salt solution (> 500 mM), both hydration and ion exchange can occur within several pore volumes of flow. GCLs were permeated with solutions
ranging from 5 mM to 500 mM. If permeated with solution less than 20 mM of CaCl₂, the hydraulic conductivity was less than 3.2x10⁻⁸ cm/sec. In contrast, when permeated with solution greater than 50 mM, the hydraulic conductivity was on the order of 10⁻⁶ cm/sec. In each test, the test was run until the sodium concentration was below detection limits (until ion exchange was basically complete). Equilibrium with the more concentrated solutions was achieved in less than 45 pore volumes of flow, whereas more than 287 pore volumes of flow were required to reach equilibrium with the lower strength (<20 mM) CaCl₂ concentrations.

Solutions permeated with the lower concentration solution also measured higher final moisture content (between 98.9 and 102%). Whereas, solutions with the higher concentration measured final water contents between 72.3 and 76.1%. For comparison, GCL permeated with DI water measured a final water content of 127%. The higher water contents with the lower concentrated solutions suggest that more water remains bound to the bentonite when ion exchange occurs slowly. The presence of this bound water results in lower hydraulic conductivity when ion exchange occurs slowly. Further, the presence of this bound water results in lower hydraulic conductivity when ion exchange is complete.

When permeated with a 12.5 mM CaCl₂ solution, the GCL maintained a low hydraulic conductivity, on the order of 2.3x10⁻⁸ cm/sec after 1,599 days of permeation. The final water content after the test was 115%. However, when allowed to air dry to a moisture content of 50%, the hydraulic conductivity quickly increased several orders of magnitude to 4.9x10⁻⁶ cm/sec. This illustrates the potential issue with GCLs in final cover applications, where the GCL may dry to a lower moisture content with time. It should be
noted that both cation exchange and dehydration occurred for the GCL to see an increased hydraulic conductivity. If in contact with a sodium rich solution and dehydrated, upon rehydration, the GCL would have maintained a low hydraulic conductivity.

Figure 6. Hydraulic conductivity vs. time with 12.5 mM CaCl$_2$ Solution and induced wetting-drying cycle

3.9 Meer and Benson (2007) – Hydraulic Conductivity of Geosynthetic Clay Liners Exhumed from Landfill Final Covers

GCLs were exhumed from four landfills, three in Wisconsin and one in Georgia. Three of the covers (Sites D, N, O) were GCL-only barriers (i.e., no overlying geomembrane), and were not geomembrane/geofilm-laminated GCLs. One landfill in Wisconsin (Site S) did contain a separate geomembrane overlying the GCL. Cover soils were also tested in accordance with ASTM D 6141, to evaluate the effluent solution for concentrations of Calcium, Magnesium, Sodium, and Potassium. Synthetic rainwater was used as the permeate solution.
Swell index tests were conducted on bentonite from new GCL and exhumed GCLs, in accordance with ASTM D 5890 using DI water. Swell tests were also performed using the solution produced from leaching the cover soil with the synthetic rainwater. In addition to swell tests, hydraulic conductivity tests, using falling headwater-constant tailwater method were conducted. A 10 mM CaCl$_2$ solution was used as the permeant liquid, to replicate conditions representative of hard tap water. The difference between hard tap water and DI water was approximately 3.6 times (1.4x10$^{-6}$ cm/sec vs. 5.1x10$^{-6}$ cm/sec) with the exhumed sample. Hence, the lack of sensitivity to the permeant fluid reflects the abundance of calcium in the exhumed GCL specimen, as a result of cation exchange.

The exhumed GCLs had hydraulic conductivities between 5.2x10$^{-9}$ cm/sec and 1.6x10$^{-4}$ cm/sec, a difference of nearly five orders of magnitude. The swell indices for the exhumed GCLs are similar to those of calcium bentonite (6-10 mL/2g). In comparison, the swell index of sodium bentonite is at least 24 mL/2g. The fraction of sodium in the exhumed specimens ranged from 0.02 to 0.29. The calcium mole fraction ranged from 0.43 to 0.78, and magnesium ranged from 0.09 to 0.21. In contrast, a new GCL specimen contained a sodium mole fraction between 0.65 and 0.74, which demonstrates the abundance of exchangeable divalent cations. The amount of calcium for sodium replacement directly corresponds to the swell index. The less exchange of calcium for sodium, the higher the swell index.

The least amount of cation exchange occurred at Site S, which contained a sodium mole fraction between 0.18 and 0.29. The GCL at this site contained an overlying geomembrane. Despite this, the GCL was still altered and its hydraulic performance was affected. Because the overlying geomembrane would have prevented pore water from
the overlying soil from hydrating the GCL, it is suspected that diffusion from the underlying subgrade soil largely contributed to the cation exchange.

There is not a correlation between the exchanged sodium mole fraction and hydraulic conductivity. GCL that is fully exchanged with calcium can still maintain a relatively low hydraulic conductivity (on the order of $2 \times 10^{-8}$ cm/sec). Accordingly, there is another mechanism that caused the very high hydraulic conductivity values. As noted by others (Lin and Benson, 2000; Egloffstein, 2001 and 2002; and Benson et al., 2006), the hydraulic conductivity is due to both replacement of sodium for calcium and magnesium, as well as dehydration of the bentonite. The dehydration of the bentonite will remove the strongly bound water molecules in the interlayer region present from the initial hydration when sodium was the dominant exchangeable cation. Additionally, dehydration will cause the formation of desiccation cracks that do not heal during rehydration when the bentonite is converted into calcium and magnesium bentonite(s). The strongly bound water in the interlayer is largely responsible for the low hydraulic conductivity of the exchanged bentonite with the dilute calcium solutions. The change in hydraulic conductivity is evident when the GCL has a gravimetric water content of less than 85 percent, with measured hydraulic conductivities between $10^{-6}$ and $10^{-4}$ cm/sec. As the GCL’s gravimetric water content exceeds 100 percent, the hydraulic conductivity decreases to between $10^{-8}$ and $10^{-7}$ cm/sec.

Thickness is another indicator of hydraulic performance. GCLs with higher water contents will maintain higher swell indices, which result in lower hydraulic conductivities. For instance, of the GCLs exhumed, the one with the highest water content, also
maintained the lowest hydraulic conductivity, and had a greater thickness compared to GCLs with lower water contents and higher hydraulic conductivities.


Based on the 2007 research by Meer and Benson, which suggested that significant increases in hydraulic conductivity can occur in response to wet-dry cycling when the percolating water is dominated by multivalent cations, this study further evaluated the hypothesis that varying the concentrations of multivalent to monovalent cations would result in varying degrees of alteration in hydraulic conductivity.

Bentonite and GCL specimens were subjected to wet-dry cycling using solutions having different relative abundance of monovalent and divalent cations (sodium to calcium). The hydraulic conductivity and swell index were measured after each cycle. The results were related to the RMD (ratio of monovalent to divalent cation) values.

Solutions for this program were devised based from 11 soils sampled from the surface layer of landfills throughout the United States to obtain an average ionic strength and RMD values. GCLs were tested with three different ionic strengths, 0.005, 0.011, and 0.025 M. RMD values included 0.007, 0.07, 0.14, and 0.7 M$^{1/2}$.

GCL samples were then placed in a permeameter and allowed to hydrate for 48 hours using the various permeant solutions, under no hydraulic gradient. After hydration, each specimen was permeated for 30 days. After permeation, the GCL specimens were air dried until the weight of the GCL did not change. No overburden pressure was applied during drying, and as indicated by Meer and Benson (2007), overburden pressure had no
noticeable effect on hydraulic performance. Seven to ten days were typical for the sample to air dry, after which the GCL had an approximate water content between 20 and 30%. GCL specimens were subjected to 5-9 wet-dry cycles using this method. After the final hydration cycle, the thickness, water content, and swell index of the bentonite were determined, as was composition of the exchange complex.

With most solutions, the swell index did not change significantly after 3 to 4 cycles. Bentonite samples that maintained a high swell index recorded values of at least 23 mL/2g after repeated wetting and drying cycles. In comparison, bentonite samples that lost swell recorded swell index values less than 15 mL/2g. Bentonite samples that maintained high swell index values were hydrated with solutions having the greatest relative abundance of monovalent cations, or solutions having an RMD equal to 0.7 M$^{1/2}$. Bentonite samples that experienced loss in swell index were hydrated with solutions having RMD values less than 0.07 M$^{1/2}$. In these samples, the bentonite experienced exchange of sodium for calcium with the increasing number of wet-dry cycles. The rate at which the exchange occurs dependent on the ionic strength of the solution. More rapid replacement occurs with higher ionic strength solutions. Solutions tested with RMD values of 0.007 M$^{1/2}$ experienced hydraulic conductivity increases by 4-5 orders of magnitude. Consistent with the high swell index, specimens subjected to wetting and drying with solutions consisting of RMD 0.7 M$^{1/2}$ maintained a consistently low hydraulic conductivity, regardless of ionic strength or number of wetting and drying cycles. Mole fractions of calcium and sodium in the final GCL specimens demonstrate the effect of cation exchange with the lower RMD solutions.
Desiccation cracks were observed in each sample, regardless of solution. However, for samples subjected to the higher 0.7 M$^{1/2}$ RMD solution, the desiccation cracks swelled shut during rehydration. Specimens with the lower RMD did not completely close – consistent with the swell and hydraulic conductivity test results, and consistent with calcium bentonite’s inability to swell to the same extent that sodium bentonite can.

Figure 7. Wetting-drying cycles vs. k with varying RMD/Ionic strength solutions
IV. EQUIPMENT AND EXPERIMENTAL METHODS

4.1 Introduction

To offset the effects of wet-dry cycling and cation exchange in GCLs, a program was developed to evaluate prototype polymer-modified bentonite (PMB) GCLs in conditions representative of landfill cover applications. Several prototypes were subjected to repeated wetting and drying in the most aggressive solution presented in Benson and Meer (2009), \( RMD = 0.007 \) M\(^{1/2}\) and \( I = 0.025 \) M. After a minimum of 10 cycles of wetting and air drying, samples were tested for free swell, and in some cases for hydraulic conductivity. The program initially began with one prototype PMB GCL, and grew in scope to include three additional prototypes, each subjected to a minimum of 10 wetting and drying cycles.

4.2 Materials

GCL samples were manufactured by CETCO, based in Hoffman Estates, Illinois. Standard bentonite-based GCLs were used in the initial part of the study in order to confirm that the test method was accurate, and that the results with bentonite were consistent with Benson and Meer (2009). Following the initial round of baseline tests, additional samples were added to the study. In each case, the GCL consisted of bentonite or polymer-modified bentonite clay encased between a woven and a nonwoven geotextile, which were needle-punched together for reinforcement. Bentonite-based GCLs are common within the industry, and use naturally occurring sodium bentonite, generally mined in Wyoming or the Dakotas. Each polymer-modified GCL sample contained a different polymer and loading. The clay-polymer blends tested in this study
are specific to the manufacturer, and specific details on the types of polymers and their loadings are considered proprietary. Several geotextile variations are available for GCLs. The types of geotextiles are largely dependent on project shear strength requirements, which is independent of this study. This study is focused on chemical compatibility and hydraulic performance of prototype GCLs.

The initial intent of the testing program was to evaluate one particular prototype polymer-modified bentonite. The study grew in scope as new products were developed, and additional samples were added to the program. For the purposes of this study, the polymer-modified bentonite GCLs will be categorized as PMB-1, PMB-2, PMB-3, and PMB-4. The bentonite-based GCL will simply be labeled Bentonite.

4.3 Test Solutions

Deionized water was used for the first round of testing to confirm that the test method was accurate. After this was confirmed, the test solution target was an RMD of 0.007 $M^{1/2}$ and an ionic strength of 0.025 M. RMD is defined as $M_m/M_d^{1/2}$, where $M_m$ is the total molarity of the monovalent cations, and $M_d$ is the total molarity of the multivalent cations in the solution. The RMD value is a ratio of the monovalent cations to the square root of the multivalent cations in solution. Sodium chloride and calcium chloride were used to obtain the desired RMD and ionic strength values. It was calculated that 0.0369 grams of sodium chloride and 0.9008 grams of calcium chloride would need to be added to one liter of deionized water. Samples were tested periodically using Inductively Coupled Plasma (ICP) to measure cation concentrations for accuracy.
4.4 Methods

GCL samples were cut to dimensions of 20 cm x 20 cm (8” x 8”). One of the challenges with working with bentonite and polymer-modified bentonite clays is their high swelling capacity. As the clay hydrates, its swell potential can be significant, especially under low confining stress. A particular challenge with this testing was preventing the clay from swelling through the edges of the GCL specimens. To prevent this, silicon caulk was applied to the edges of the GCL specimens. The silicon was allowed to dry for at least one day prior to placing the GCL specimens in DI water or the salt solution. GCL moisture was measured by oven drying to obtain the initial dry unit weight of each GCL specimen. The mass of the geotextiles and silicon were recorded and subtracted from the GCL specimens, and the moisture content of the bentonite was measured.

Initial prototype samples were submerged between two geonet or geocomposite samples, simply rubber banded together. Geonets and geocomposites are used for drainage applications, and consist of a high density polyethylene (HDPE) geonet between two nonwoven geotextiles (geocomposite if it contains the geotextiles). These materials would provide some stability for the GCLs and provide very light and uniform confining pressure. In real world applications, a minimum of 0.3 meters, and in most cases at least 0.6 meters of cover soil are installed over the GCL or composite system. Hence, the low confining pressure provided by the geocomposite is considered conservative. Generally speaking, more confining stress for a GCL would yield lower hydraulic conductivity values. As the void space between the bentonite platelets decreases, the hydraulic conductivity of the bentonite and the GCL decreases. This has been demonstrated Petrov and Rowe
In repeated test series, weights were applied to the top of the geocomposites to simulate modest confining pressure provided by the cover soil.

GCL samples were allowed to hydrate for a minimum of 48 hours in the test solution (either DI water or the salt solution). 48 hours of GCL hydration is the industry standard for hydraulic conductivity testing per ASTM D5887. Plastic bins were used for hydration in order to eliminate the possibility of corrosion by salt if metal pans were used. New solution was used for each hydration cycle in order to maintain a constant chemistry, and eliminate the possibility of the solution chemistry changing due interactions with the minerals within the GCL.

Immediately after each hydration cycle, the bentonite moisture content was determined by weighing the GCL. Moisture content can be a one way to evaluate the GCL’s hydraulic performance. The more water that the bentonite or polymer-modified bentonite clay absorbs, the more likely it will maintain a high swell index and a low hydraulic conductivity. This is consistent with previous research which demonstrated calcium bentonite’s lower moisture content and higher hydraulic conductivity as compared
to sodium bentonite (Benson, Thorstad, 2007). GCL samples that experienced a constant moisture content after each hydration cycle would likely maintain a constant hydraulic conductivity. In contrast, GCL samples that experienced a decrease in moisture content after each cycle were more likely to see a decrease in hydraulic performance.

Six separate standard bentonite-based GCLs were each tested with DI water and the salt water solution, three samples in each solution. Samples were terminated after 4, 7, and 10 cycles, and tested for swell index after each cycle. The same procedure was used for the first prototype polymer-modified GCL.

Swell index is an ASTM test method (ASTM D5890) for bentonite and GCLs. The method requires 2 grams of dry bentonite, ground to a powder form with 100% of the clay passing the 100 mesh U.S. Standard Sieve, and a minimum of 65% passing a 200 mesh U.S. Standard sieve. The bentonite sample would be oven dried at approximately 105°C. A common method to grind the bentonite is to use a mortar and pestle, which was used in this study. After 2 grams of powdered bentonite is collected, small increments (less than 0.1 g) of clay are added to a 100 mL graduated cylinder, filled with 90 mL of the selected water. In most cases, deionized water is used. In this study, both deionized and salt water were used as the reagent liquids. The industry standard for bentonite in DI water is a minimum swell of 24 mL/2g of bentonite, which will generally yield a hydraulic conductivity that is less than $5 \times 10^{-9}$ cm/sec. As we found in this study, the polymer-modified bentonites behave very differently than standard bentonite does, and swell tests may not provide a clear correlation with hydraulic performance. Nevertheless, a constant or decreasing swell index in relation to the number of wetting and drying cycles should
give an indication of how much impact the polymer-modified clay is undergoing due to the conditions.

Samples were allowed to air dry to a maximum of 40% moisture content, and in many cases lower, consistent with Benson and Meer (2009). GCL samples typically dried within one week. To expedite drying, a dehumidifier was used in some cases. An oven was not used to dry the samples for this study. Using the air drying method is justified and should be considered conservative. Take et al (2012) measured desiccation cracking using X-ray imagery of both air dried and oven dried GCL samples. They found that desiccation will occur via either method. However, they also found that the desiccation cracks between the intact bentonite were larger in width in the air-dried specimens as compared to the oven dried specimens.

Upon completion of the wetting and drying cycles, in addition to a swell index test, samples were also tested for hydraulic conductivity with the low RMD salt solution in
accordance with ASTM D6766, with the exception that the samples were not tested to chemical equilibrium. ASTM D6766 is a modified version of ASTM D5887 which uses DI water. Using the same salt solution for the hydraulic conductivity test would be conservative, and representative of field conditions.

Figure 11. ASTM D6766, Hydraulic Conductivity Test
V. RESULTS AND DISCUSSION

Tests were initiated with bentonite GCL samples subjected to a series of wetting and drying cycles in DI water to confirm that the test procedure was correct. After being subjected to several cycles, with minimal confining stress, due to bentonite’s mobility a significant amount of clay was lost through the geotextiles. For this reason, testing was terminated after 9 cycles, instead of the intended 10 cycles. The loss of bentonite was observed visually in the pan, as well as observed loss of mass after repeated cycles. However, the loss of mass in the GCL specimen in this case was not due to cation exchange, where the bentonite doesn’t absorb as much water with repeated cycling, but simply due to the loss of bentonite, and as a result, less water was absorbed by the GCL specimen as a whole. This was further confirmed by free swell tests, which tested consistent with a new GCL.

Figure 12. Bentonite moisture content vs. cycle number with DI water
In each case, the moisture content of the bentonite was between about 225% and 350%. Certain cycles allowed the GCL to hydrate for longer than 48 hours, and as a result higher moisture contents were recorded for the bentonite. Following termination of each sample after their respective cycles (4, 7, and 9), swell index was measured. A portion of the GCL was cut to remove the bentonite, and was oven dried overnight. Following ASTM D5890 procedures, the bentonite was ground to pass the 100 mesh, and tested for swell index. In each case, the bentonite exhibited a consistent swell index of approximately 24 mL, indicating that wetting and drying on its own did not affect the bentonite with repeated wetting and drying cycles. These results were consistent with Shan and Daniel, 1991.

The next set of tests included the same bentonite-based GCL subjected to repeated wetting and drying, only this time a $\text{RMD} = 0.007 \ M^{1/2}$, $I = 0.025 \ M$ salt solution was used instead of DI water. A clear downward trend in the bentonite's ability to absorb water was observed with repeated wetting and drying cycles in the salt solution. This trend indicated that cation exchange was taking place, and that the bentonite's ability to absorb water and swell had decreased.
Bentonite’s ability to swell after the repeated wetting and drying cycles in the salt solution was measured after each sample was terminated. After 4 cycles of wetting and drying, the bentonite free swell was 10 mL, and decreased to 8.5 mL after 7 cycles, and to 7.5 mL after 10 cycles – representative of calcium bentonite’s low swell capacity. This demonstrated that the sodium bentonite was essentially converted into calcium bentonite. Further, the decreased moisture contents and swell index values were consistent with Benson and Meer (2009), where the GCL’s hydraulic conductivity increased several orders of magnitude after just two cycles. Hydraulic conductivity tests confirmed the poor hydraulic performance. Samples were tested in accordance with ASTM D5887 with DI water, and results for all three samples demonstrated high hydraulic conductivity rates, on the order of $10^{-5}$ cm/sec. These tests were run under a relatively low confining stress.
of 34 kPa (5 psi). With higher confining stress, the hydraulic conductivity would be expected to decrease (Petrov and Rowe, 1997).

Testing proceeded with the first prototype PMB GCL (PMB-1) in the salt solution. For this trial, the free swell of the virgin polymer-bentonite clay was measured for comparison. The same procedure as outlined in ASTM D5890 was used for this clay sample. Upon applying very small amounts of the dried polymer-bentonite clay, the mixture behaved very differently from standard bentonite, and measured a very high swell index with DI water. In fact, only 1.3 grams were added, with a measured swell of over 85 mL in DI water. The test was repeated, but the salt water solution was used as the reagent solution. Using salt water, the swell with PMB-1 measured 56 mL with 2 grams of polymer-modified clay.

Samples of PMB-1 were subjected to 4, 7, and 10 wetting and drying cycles in salt water. Moisture content was recorded after each sample was tested to evaluate the impact that wet-dry cycles in combination with cation exchange would have on this particular prototype GCL.
This material seemed to sustain a reasonably constant moisture content through 5 or 6 cycles, but experienced a rapid drop soon after to levels that were similar to standard bentonite after 10 cycles. Samples subjected to 4 and 10 cycles were tested for swell index. After 4 cycles, the swell was similar to the virgin material, which is consistent with the still high moisture content in the graph above. After 7 cycles, the swell index experienced a drop to 68 mL with DI water, and just 10 mL with the salt water. Swell was not measured after 10 cycles; however, it was clear that the GCL had failed. This was confirmed with hydraulic conductivity tests on all three specimens. The hydraulic conductivity of PMB-1 after 4 cycles was low, on the order of $6 \times 10^{-10}$ cm/sec when tested with the same salt solution per ASTM D6766. The test ran for several months, without an increase in hydraulic conductivity. The test was not run to chemical equilibrium. However, after 7 and 10 cycles, the hydraulic conductivity had increased by several orders of
magnitude, to the order of $10^{-5}$ cm/sec. Hence, this particular polymer-modified clay blend was deemed not compatible for use in capping applications.

It should be noted that swell index is not necessarily representative of good or bad hydraulic performance with polymer-modified bentonites. While there is a clear correlation between swell index and hydraulic conductivity with standard bentonite, the addition of polymer may yield a low hydraulic conductivity value, despite a lower swell index in some cases. For this reason, hydraulic conductivity testing is often recommended when polymer-modified bentonite GCLs are tested for compatibility. PMB GCLs are seeing increased use in more chemically aggressive applications, where standard bentonite does not provide the required hydraulic performance. However, under these conditions, the GCL maintains a relatively high moisture content, whether because it is installed as a bottom liner of a facility, or because the GCL is typically covered by a geomembrane, as is often the case in a landfill cover. The presence of potential wetting and drying conditions are still a unique element for these materials.

Tests on PMB-1 were repeated, but this time with a 22.5 kg (50 lb) weight applied to the sample during each hydration cycle. Applied to the 20 cm x 20 cm, this is representative of a modest pressure of just 5.3 kPa (0.78 psi). The trend in moisture content, while slower with the weight applied, was still downward.
The next set of tests included three additional polymer-modified bentonite GCLs, labeled in this study as PMB-2, PMB-3, and PMB-4. These samples were subjected to a minimum of 10, and in some cases 20, wetting and drying cycles in the same salt water solution used above. A clear trend was not observed with respect to the samples' moisture contents. Sample PMB-4 saw an unusually sharp dip in moisture content around cycle 8, only to see a rebound later to close to the initial moisture content. This may be a function of the length of time the sample was allowed to dry. The sample was allowed to dry for over two weeks, to a moisture content in the single digits. Upon rehydration, the sample hydrated to only a fraction of the initial moisture content. However, after subsequent cycles, the moisture content increased. Sample PMB-2 maintained a relatively constant moisture content. Sample PMB-3 experienced a downward trend. However, this was also largely a function of lost polymer and/or bentonite. Through repeated cycles, and the

Figure 15. PMB-1 moisture content vs. cycle number with 0.007 M$^{1/2}$ RMD water and 5.3 kPa weight applied
mobility of the particular polymer used, mass was lost from the GCL sample through the openings in the geotextile, contributing at least in part to the decreasing mass of the GCL.

Figure 16. PMB-2, PMB-3, and PMB-4 moisture content vs. cycle number with RMD 0.007 M$^{1/2}$ water

Swell index was measured for PMB-2 after the 10 wetting and drying cycles, with measured values of 41 mL/2g in DI water and 19 mL/2g in the RMD 0.007 M$^{1/2}$ salt water solution. Both results are encouraging, although the high swell values needed to be confirmed with hydraulic conductivity test results.

PMB-3 was measured for swell index after 10, 15, and 20 cycles. Swell tests were conducted with both DI water and the salt solution as the reagent liquids.
A significant decrease in swell between 10 and 20 cycles was not evident for PMB-3. PMB-4 was tested for swell index prior to any testing commenced with the solution, with a measured index of 32 mL. After 15 cycles, the swell index decreased to 21 with the same salt solution. It is not yet clear if swell index tests are appropriate for polymer-modified bentonite clays. However, based on the hydraulic conductivity test results, a free swell of approximately 20 mL/2g with the permeation liquid appears to provide a reasonably low hydraulic conductivity.

The polymer modified GCLs recorded hydraulic conductivity values between $2.3 \times 10^{-9}$ cm/sec (PMB-4) and $5.2 \times 10^{-8}$ cm/sec (PMB-3). It should be noted that PMB-3 experienced significant loss of polymer after several rounds of hydration and drying. Despite the polymer extrusion, this value is still low by most standards.
Table 1. Hydraulic Conductivity Test Results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Hydraulic Conductivity</th>
<th>Elapsed Time</th>
<th>PVF</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMB-2</td>
<td>$6.7\times10^{-9}\text{ cm/sec}$</td>
<td>215 hrs</td>
<td>1.13</td>
</tr>
<tr>
<td>PMB-3</td>
<td>$5.2\times10^{-8}\text{ cm/sec}$</td>
<td>59.8 hrs</td>
<td>7.71</td>
</tr>
<tr>
<td>PMB-4</td>
<td>$2.3\times10^{-9}\text{ cm/sec}$</td>
<td>219.6 hrs</td>
<td>1.33</td>
</tr>
</tbody>
</table>

Due to the higher hydraulic conductivity of PMB-3, more pore volumes of flow (PVF) were able to permeate through the sample in a shorter time period. These tests have initially been run for a relatively short period of time. The typical criteria for compatibility testing is ASTM D6766, which requires that the test be run until the outflow fluid chemistry is about equal to that of the inflow fluid chemistry. Accordingly, while
extended testing is required to validate the long-term performance of these materials, these tests are a good indication of the GCL’s performance, and an encouraging sign that the samples can maintain a low hydraulic conductivity despite repeated cycles of wetting and drying in a calcium-rich environment.
VI. CONCLUSIONS

The use of GCLs in cover applications has been limited due to the nature of sodium bentonite’s affinity for cation exchange with divalent cations combined with conditions that promote GCL desiccation. The combination of cation exchange and desiccation can result in significant increases in a GCLs hydraulic conductivity, essentially resulting in a poor hydraulic barrier. Traditional methods used to offset these effects include installing an overlying geomembrane, which would help prevent GCL desiccation, or to install a GCL over sodium rich soils in order to prevent cation exchange. Sodium rich soils are rarely encountered in the environment. Including an overlying geomembrane adds additional material and installation costs.

To help improve GCL performance in cover applications, a series of tests were performed to evaluate prototype polymer-modified GCLs in cover applications. GCL samples were subjected to repeated wetting and drying cycles in a calcium-rich solution. After a minimum of 10 cycles, clay samples were tested for free swell and for hydraulic conductivity. Initial results demonstrate that a polymer-modified GCL can have a low hydraulic conductivity despite the combined effects of repeated wetting and drying and cation exchange. Three of the four samples tested maintained a high swell index (~20 mL/2g) and low hydraulic conductivities (2.3x10^{-9} cm/sec to 5.3x10^{-8} cm/sec).
REFERENCES


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