Robust Ion Exchange Resistant GCLs for Mining Applications

Michael S. Donovan[1], John Allen[2], Dennis Wind[3] and Barbara Gebka[4]

[1]Global R&D Director
[2]Technical Services Manager
[3]Lab Technician
[4]Scientist
Corresponding author: michael.donovan@mineralstech.com

ABSTRACT

Geosynthetic clay liners (GCLs) have been used for a quarter century as a substitute for the compacted clay component of composite liners in various industrial applications. The primary use of GCL liners has been for municipal solid waste landfills. GCLs have seen limited use in other applications, such as liners for mining applications that involve high salinity and or high/low pH leachates, due to the chemical compatibility limitations of the base bentonite. The leachates involved in these studies were representative of those encountered in low pH mining applications, like copper heap pads. The hydraulic performance of several different polymer/clay systems were compared against a range of leachates representative of heap leaching. Through this work it was found that the hydraulic conductivity was dependent on factors such as the leachate chemistry, polymer content as well as other parameters such as effective stress.

Keywords: heap leach pad liner, geosynthetic clay liner, polymer modified bentonite, chemical compatibility, hydraulic conductivity, ion exchange resistance.

INTRODUCTION

GCLs have been successfully used to reduce leakage from composite liner systems for many years. Depending on the installation scenario, traditional sodium bentonite-based GCLs can demonstrate reduced effectiveness in conditions that reduce the swelling potential of the bentonite. Conditions such as low/high pH, elevated saline levels or conditions involving high calcium can supress the osmotic swelling of the anionically charged clay platelet surfaces. In particular, calcium ions function to bridge the bentonite clay platelets due to their divalent cationic charge. Some applications, such as exposed liners or landfill caps, can involve conditions that have low effective stress applied to the liner and the opportunity for repeated wet/dry cycling.

Research by Scalia and Benson (2011) has shown that sodium bentonite based GCLs can maintain their low hydraulic conductivity after complete ion exchange, but the bentonite must be prehydrated with fresh water and stay confined by high effective stresses. One method that has been proven effective to better protect the bentonite from the effects is the use of geomembranes. Geomembranes can promote hydration of the bentonite and can reduce the exposure to calcium from the cover soil. There exists a need for geosynthetic hydraulic barriers that retain their properties when placed in environments where the conditions cannot be controlled. This work is aimed at

developing barrier liners for large projects where the rapid scheduling of earth works can add to the complexity of the project.

The aim of this study is to evaluate a new class of polymer modified GCLs (PMG) that withstand extreme conditions such as wet/dry cycling in the presence of calcium as well as extremely low pH. The evaluations we have done relate the specifications of the PMG (such as polymer content) to the performance in simulated field conditions. The data shows a clear relationship with index tests such as LOI, free swell and fluid loss to the anticipated hydraulic performance of the product. This new class of polymer will allow for much easier qualification of the performance in a given condition. The testing also shows the response of hydraulic conductivity to effective stress. The intent of this portion of the study was to simulate mining field conditions where the material is covered with large amounts of soil or ore. These new GCLs will allow for more flexibility for the scheduling of the earth work for large projects as they reduce the need for immediate covering and confinement of the GCL in the field.

EXPERIMENTAL

Inductively Coupled Plasma (ICP)
ICP testing was performed on a Thermo Iris Intrepid ICP-OES unit equipped with a radial argon torch. Teva 1.6.5 software was used to collect the data. The leachate and permeate samples were diluted 1 to 100 with DI water. The ICP was calibrated with standard electrolyte solutions of 5, 50, 100 and 200 ppm prior to analysis.

Loss on Ignition
The LOI procedure was described elsewhere by the author (Donovan GeoAmericas 2016).

Hydraulic Conductivity
Hydraulic conductivity tests on PMG specimens in acidic conditions were conducted in a flexible-wall permeameter using a falling headwater / constant tail water method described in ASTM D6766. The PMGs tested at low effective stress were hydrated with permeant liquid in the permeameter for 48 hr at an effective confining stress of 35 kPa. The PMGs tested at high effective stress were hydrated with permeant liquid in the permeameter for 48 hr at an effective confining stress of 90 kPa. During the tests, the hydraulic gradient was set at approximately 150. Influent for the specimen was introduced using a burette. The permeate was collected in sealed individual vials. Perm testing was conducted for varying lengths of time depending on the hydraulic properties of the sample.

Hydraulic conductivity tests on GCL specimens in calcium chloride solutions were conducted in a flexible-wall permeameter using the falling headwater / rising tail water method described in ASTM D6766. The GCLs were hydrated with permeant liquid in the permeameter for 48 hr at an effective confining stress of 35 kPa. During the tests, the hydraulic gradient was set at approximately 150. Influent for the specimen was injected using a bladder accumulator. Permeate was collected using a bladder accumulator. After approximately ~150 mL of flow into the accumulator, the bladder accumulator was emptied and a portion of the leachate was stored in screw cap plastic vials for analysis. Select samples were tested for permeability against the synthetic copper leachate (L5) after 15 PVF. For this testing, the bladder accumulators were

cleaned and filled with the synthetic copper (L4) leachate. Leachates L4 and L5 are described below. The effective stress was increased to 200 kPa and the permeability tests were restarted. The estimated hydraulic gradient was 200 for these examples.

Leachate Characterization
Electrical conductivity (EC) was measured using a Mettler Toledo SevenGo Pro conductivity meter. The EC was expressed as microSiemens per centimeter (μS/cm). The pH of the leachates and permeates were measured using an Oakton Ion 700 pH meter equipped with an Oakton Acorn model 35811-98 probe. Chloride content was estimated by QuanTab® Test Strips. The sulfate/bisulfate content was estimated by the sulfur content detected by ICP.

Ionic Strength (I) and Ration of Ratio of Monovalent to Divalent Ions (RMD):
The calculation of ionic strength and the ratio of monovalent to divalent ions is described elsewhere by the author (2016). The ionic strength, I, of a solution is a function of the concentration of all ions present in that solution, where c_i is the molar concentration of ion i (mol·dm^{-3}), z_i is the charge number of that ion, and the sum is taken over all ions in the solution. Relative abundance of monovalent and multivalent cations was characterized by the RMD of each test solution. The RMD is defined as the ratio of the total molarity of monovalent cations to the square root of the total molarity of multivalent cations at a given ionic strength. ICP data were used to compute the RMD of the leachate.

Polymer Modified Geosynthetic Clay Liner (PMG)
Samples of PMG-A were produced by CETCO® on commercial production equipment. The clays were granular Western sodium bentonite type clays with a maximum 10% retained on 18 mesh (850 microns) and maximum 15% passing 200 mesh (75 microns). The average inherent moisture content of the bentonite used was 10-12%. The polymer type and loading is proprietary information developed by the authors. As such, we will describe the product differences in terms of an LOI value. The polymer/bentonite ratio was varied to hit an LOI range of 3.8% to 10.6%. The samples were produced at total active mass per unit area of between 0.8 and 0.9 lbs/ft. The samples were produced with nonwoven cap and base textiles.

Ion Exchange:
GCL samples were prepared for ion exchange as outlined by Goldenberg et. al. (2015). The samples were cut to dimensions of 20 cm x 20 cm (8"x8"). 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 the salt solution. Initial prototype samples were submerged between two geonet or geocomposite samples, simply rubber banded together. At least 4 samples of each PMG type were subjected to wet/dry cycles. The samples were contained in individual plastic trays containing the ion exchange solution. The GCL samples hydrated for a minimum of 48 hours. New solution was used for each hydration cycle. Samples were removed from the leachate and allowed to air dry for one week at ambient temperature and 50% relative humidity or less. Upon completion of the wetting and drying the active components of the PMG removed for index testing. The isolated materials after the various wet/dry cycles were tested for swell index (according to ASTM D 5890-modified for polymer treat) and fluid loss (according to ASTM D 5891-

modified for polymer treat) in 0.01M $CaCl_2$. Care must be taken when preparing PMG samples by milling since segregation of the polymer and clay can occur. Best practices for preparing samples are outside the scope of this work and can be made available upon request.

Leachates
Ion Exchange Leachate:
The leachate used for ion exchange was prepared as described by Goldenberg et al. (2015) The solution had a target RMD of 0.007 $M^{1/2}$ and ionic strength of 0.025 M. Sodium chloride (0.0369 grams) and calcium chloride (0.9008 grams) were dissolved in one liter of deionized water. Samples of the leaching solution were tested periodically using inductively coupled plasma (ICP) spectroscopy to follow the change in ion concentration as the exchange process occurred over time.

Calcium chloride leachate for hydraulic conductivity testing:
The PMG samples were tested for hydraulic conductivity using a 0.01 M $CaCl_2$ solution. The solution was prepared by dissolving 1.11 grams of $CaCl_2$ in 1 liter of deionized water.

Synthetic Leachates - Synthetic Copper Leachates and Phosphogypsum Leachate:
The synthetic phosphogypsum leachate L2 and the synthetic copper leachates L3 and L4 were formulated in the CETCO laboratory. The L2 leachate had a pH of 0.5 and an electrical conductivity of 171,000 µS/cm. The ionic strength of L2 was calculated to be 1.52 mol/L with an estimated RMD of 0.53 $M^{1/2}$. The L3 leachate had a pH of 1.0 and an electrical conductivity of 71,000 µS/cm. The ionic strength of L3 was calculated to be 1.99 mol/L with an estimated RMD of 0.21 $M^{1/2}$. The L4 leachate had a pH of 1.36 and an electrical conductivity of 45,200 µS/cm. The ionic strength of L4 was calculated to be 2.0 mol/L with an estimated RMD of 0.03 $M^{1/2}$. The leachate chemistry of the synthetic leachates are described below in Table 4. The recipes for the synthetics leachates used in this study are available upon request.

Field Leachates - Pregnant Copper Leachate and Phosphogypsum Leachate:
The leachate chemistry from the field samples are described below in Table 4. A phosphogypsum process leachate was also obtained from a site in Florida USA (designated as L1). The L1 leachate had a pH of 1.81 and an electrical conductivity of 24,500 µS/cm. The ionic strength was calculated to be 0.27 mol/L with an estimated RMD of 0.83 $M^{1/2}$. A copper leaching solution was obtained from a site in Nevada USA (designated as L5). The L5 leachate had a pH of 1.96 and an electrical conductivity of 45,200 µS/cm. The ionic strength was calculated to be 5 mol/L with an estimated RMD of 0.026 $M^{1/2}$.

RESULTS AND DISCUSSION

The exchange process for traditional sodium bentonite GCLs has been detailed in several studies. Meer and Benson (2009) demonstrated the impact of ion exchange on hydraulic performance of sodium bentonite GCLs can occurs after approximately 1-5 wet/dry cycles. This response was dependent on the RMD of the solution. No impact on hydraulic conductivity was observed for waters with an RMD of greater than 0.7 $M^{1/2}$.

Other research into the impact of ionic strength on hydraulic performance indicates that the ionic strengths higher than approximately 50 to 150 mmol/L can results in higher than desired hydraulic conductivities. Both of these factors can be mitigated to some extent by prehydrating the GCL with fresh water and maintaining its compaction and hydration with confinement by a cover soil. Prehydration can add an extra logistic challenge to projects in remote areas. By treating the bentonite with a new type of polymer, the GCLs can maintain their hydraulic performance through the retention of their swelling pressure and plastic nature.

For this study, five PMG blends were developed using the same polymer type. The loading of the polymer in each system is proprietary information, so we relate the differences by using loss on ignition. The lowest LOI for this study was ~3.8% and the highest LOI was ~10.6%. To track the exchange process for each system, the concentrations of sodium and calcium ion concentrations were measured in the exchange water, shown in Tables 1 and 2. Ion exchange equilibrium was the determined to be the point at which the calcium and sodium ion concentrations reached a plateau. Figure 1 shows that it takes approximately 15-20 cycles to reach equilibrium.

Table 1. Calcium concentration (ppm) in exchange water vs wet/dry cycle

	Cycle #:	11	12	13	14	15	16	17	18	19	20
	Initial Leachate:	282	285	282	288	301	309	301	309	322	318
ID	LOI (%)										
PMG-A1	3.8	278	299	278	321	333	342	335	331	368	341
PMG-A2	5.7	294	312	294	339	334	338	327	345	372	348
PMG-A3	6.7	309	316	309	333	349	364	349	350	374	359
PMG-A4	9.2	273	378	273	309	335	342	324	349	369	352
PMG-A5	10.6	287	361	287	319	341	335	327	360	363	364

Table 2. Sodium concentration (ppm) in exchange water vs wet/dry cycle

|	Cycle #:	11	12	13	14	15	16	17	18	19	20
	Initial Leachate:	23	25	23	22	27	23	23	33	30	34
ID	LOI (%)										
PMG-A1	3.8	35	36	35	34	33	33	32	36	40	41
PMG-A2	5.7	46	38	46	40	35	32	29	35	38	41
PMG-A3	6.7	44	39	44	35	33	32	31	35	39	41
PMG-A4	9.2	32	45	32	33	29	31	29	36	37	42
PMG-A5	10.6	55	57	55	42	40	35	35	43	41	46
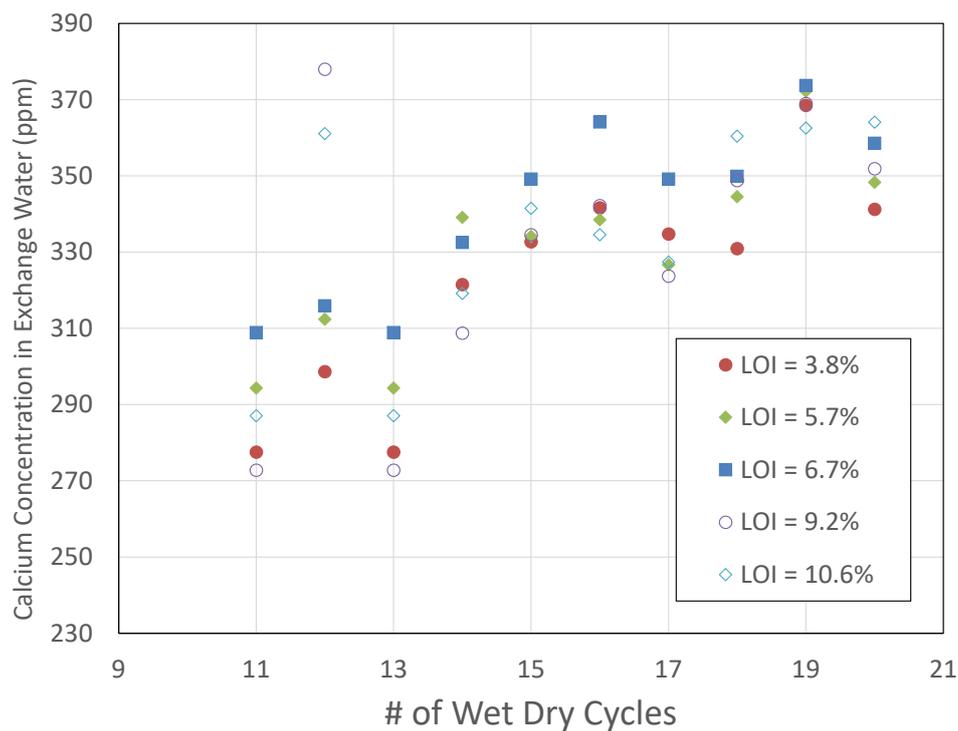
Figure 1. Calcium concentration in water bath as a function of ion exchange cycles.

To determine the influence of ion exchange on the swelling and sealing potential of the bentonite/polymer blends, the active ingredients were extracted from the PMG samples after various wet/dry cycles. Free swell and fluid loss testing was done in 0.01M $CaCl_2$ water on the extracted blends and reported in Table 3. The free swell data, represented in Figure 2, shows a steady decrease in the swell as the ion exchange progressed. Depending on the system, the reduction in free swell ranged from 48% to 61% of its starting value. Samples with higher polymer loadings exhibited higher free swell values. The free swell values for the PMGs are still much higher than obtained for pure calcium bentonite (FS= 5mL). The data for the impact of fluid loss in 0.01M $CaCl_2$ water is shown in Figure 3. Fluid loss values of virgin samples ranged from 11 to 18 mL. As the exchange process progressed, the fluid loss values increased. This increase was dependent on the polymer loading where the lowest fluid loss observed was ~34 mL. The fluid loss values for the extracted PMGs were much lower than obtained for pure calcium bentonite (FL=180mL).
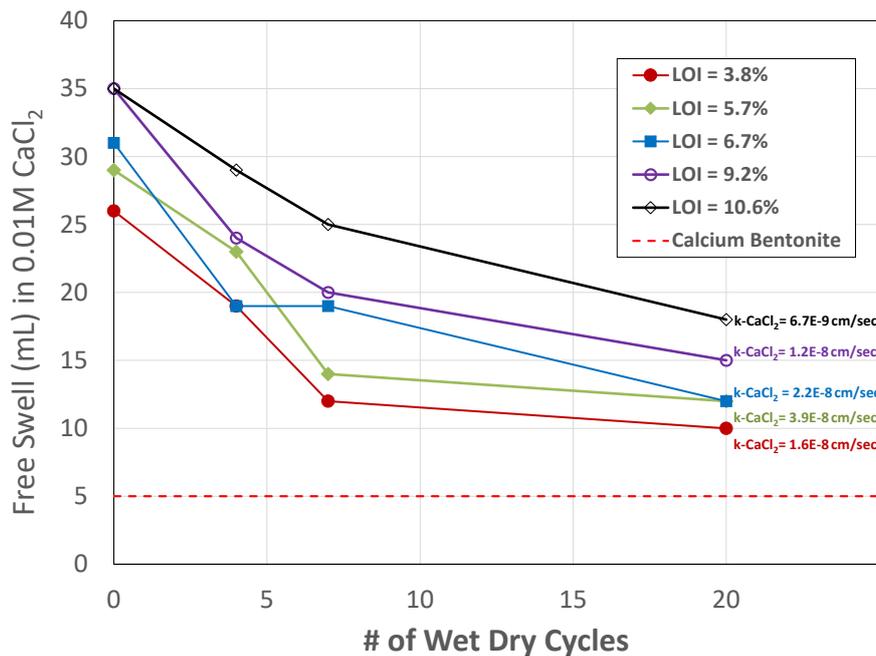
Figure 2. Free swell in 0.01M CaCl$_2$ water as a function of wet dry cycles for PMG systems with varying LOI values (ASTM D5890 modified).
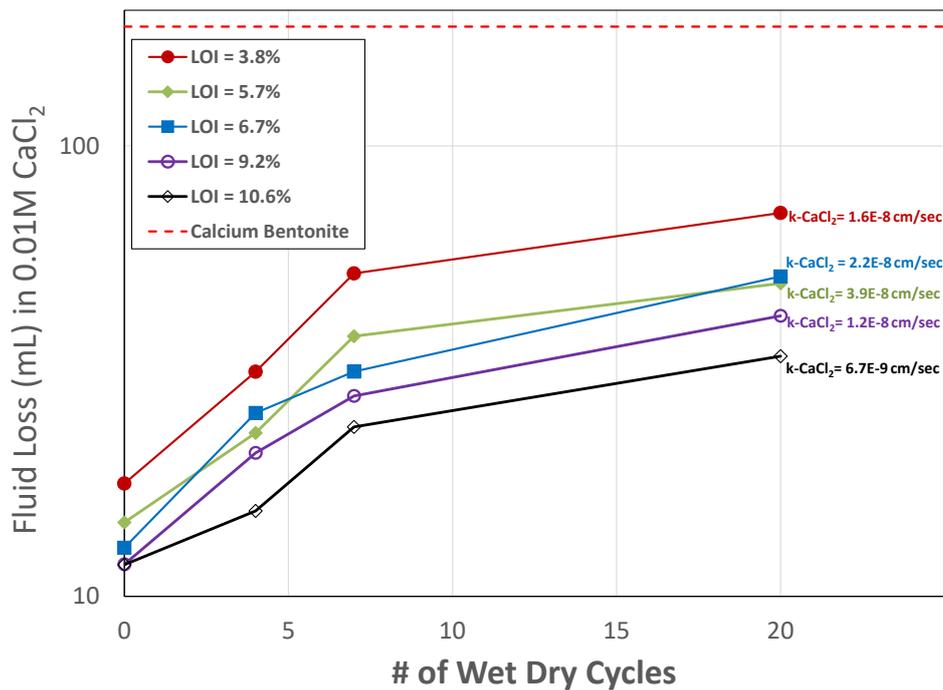
Figure 3. Fluid loss in 0.01M CaCl$_2$ water as a function of wet dry cycles for PMG systems with varying LOI values (ASTM D5891 modified).

The impact of ion exchange on the hydraulic conductivity in a calcium chloride solution was also monitored. As seen in the Meer study (2009), the impacts to the hydraulic conductivity of traditional GCLs can be seen with as few as 4 wet/dry cycles. As such our first data point was collected at 4 cycles. The data for this work is summarized in Table 3. A 0.01M CaCl$_2$ solution was chosen as the permeant solution as this was used in

prior ion exchange studies in the literature (Goldenberg 2016 and Meer 2009). Shown in Figure 4 is the hydraulic conductivity as a function of ion exchange cycle number and LOI value. The initial values for hydraulic conductivity was measured at approximately 7×10^{-10} cm/sec. After ion exchange, the hydraulic conductivity of all systems was dependent on the LOI value and was less than 4×10^{-8} cm/sec. As the LOI of the bentonite/polymer blend increased, the hydraulic conductivity generally decreased. The lowest hydraulic conductivity after 20 cycles was 6.6×10^{-9} cm/sec for PMG-A5 system, which had the highest LOI value.

Table 3. Free swell, fluid loss and hydraulic conductivity vs wet/dry cycle.

		Free Swell in 0.01M $CaCl_2$ (mL)			
System ID	LOI (%)	Cycle 0	Cycle 4	Cycle 7	Cycle 20
PMG-A1	3.8	26	19	12	10
PMG-A2	5.7	29	23	14	12
PMG-A3	6.7	31	19	19	12
PMG-A4	9.2	35	24	20	15
PMG-A5	10.6	35	29	25	18
		Fluid Loss in 0.01M $CaCl_2$ (mL)			
System ID	LOI (%)	Cycle 0	Cycle 4	Cycle 7	Cycle 20
PMG-A1	3.8	18	32	52	71
PMG-A2	5.7	15	23	38	50
PMG-A3	6.7	13	26	32	51
PMG-A4	9.2	12	21	28	42
PMG-A5	10.6	12	16	24	34
		Permeability in 0.01M $CaCl_2$ (cm/sec)			
System ID	LOI (%)	Cycle 0	Cycle 4	Cycle 7	Cycle 20
PMG-A1	3.8	6.7E-10	1.0E-08	1.9E-08	1.6E-08
PMG-A2	5.7	7.0E-10	1.0E-08	3.4E-08	3.9E-08
PMG-A3	6.7	6.7E-10	2.7E-09	2.6E-08	2.2E-08
PMG-A4	9.2	Not Measured	5.2E-09	2.6E-08	1.2E-08
PMG-A5	10.6	Not Measured	1.6E-09	3.0E-09	6.7E-09

One unique aspect of these systems is the ability to correlate index properties such as free swell and fluid loss to the hydraulic behavior. This will greatly accelerate the process by which product build can be selected. This correlation will allow for the selection of the most cost effective product for a given field condition. Shown below in Figure 5 is the relationship between free swell and hydraulic conductivity in 0.01 M CaCl2. There exists good correlation between the index properties such as free swell and fluid loss in the testing fluid and hydraulic performance against the same fluid.
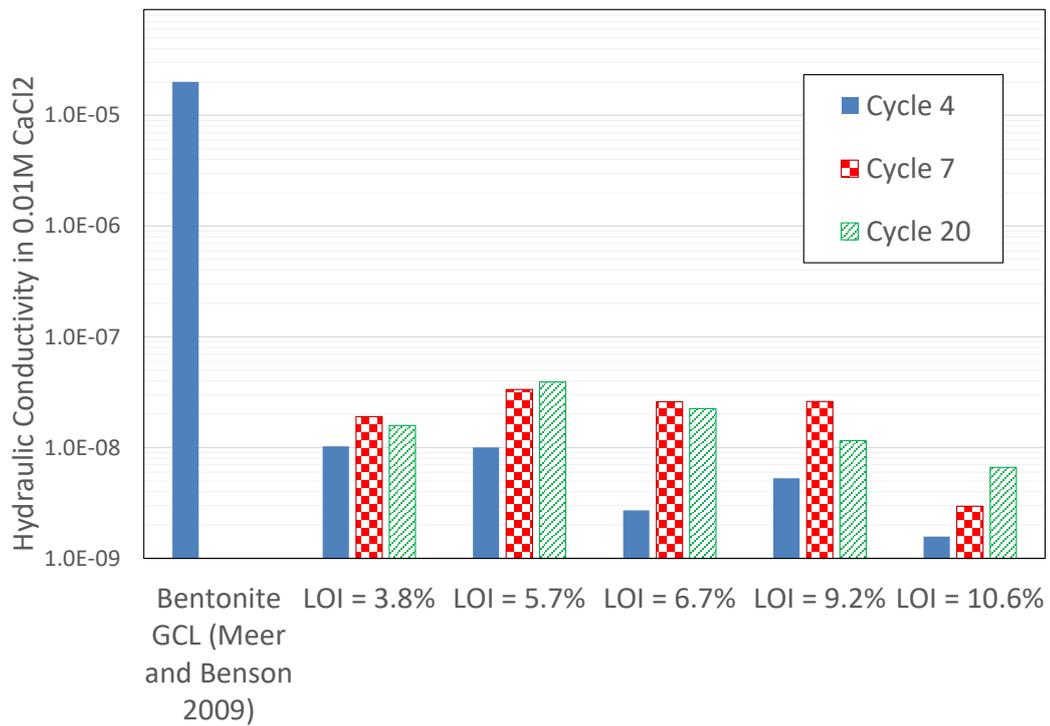
Figure 4. Hydraulic conductivity (ASTM D6766) in 0.01M CaCl$_2$ as a function of wet/dry cycle and LOI.
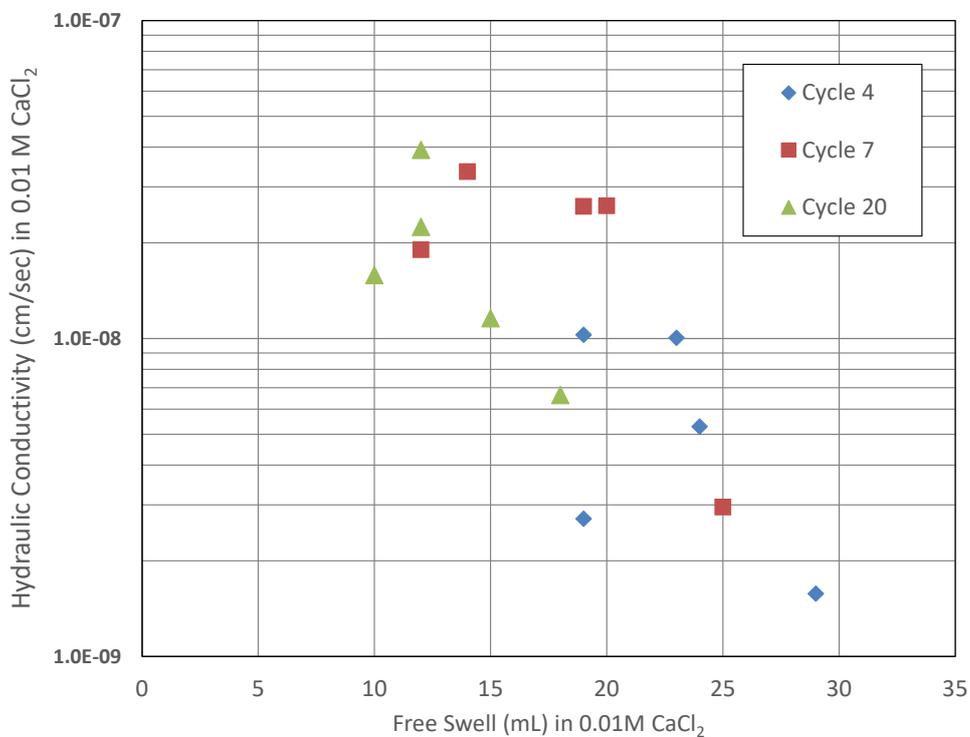
Figure 5. Hydraulic conductivity (ASTM D6766) in 0.01M CaCl$_2$ vs free swell in 0.01 M CaCl$_2$ (ASTM D5890 modified).

HYDRAULIC PERFORMANCE IN MINING SOLUTIONS

Shown below in Table 4 are the chemistries of various acidic leachates used in this study. The goal of the study was to determine the response of the various PMG-A formulations as a function of leachate chemistry/ionic strength. The leachates selected were chosen to be representative of pregnant heap leach solutions from phosphogypsum (P-GYP) or copper mining. At least one field collected leachate was tested for each mining type. The synthetic leachates were formulated in our lab.

Shown below in Table 5 are the hydraulic conductivities of the various PMG-A samples. The hydraulic conductivity data is plotted (see Figure 6) as a function of ionic strength for the various systems. For a given leachate chemistry, the hydraulic conductivity decreases for systems with higher polymer loading. Larger differences in performance were seen with the most concentrated mining leachate (Copper leachate – L5). The lowest hydraulic conductivity values at the 34.5 kPa effective stress were observed for the PMG-A5 system, ranging from 8.2×10^{-9} to 3.4×10^{-10} cm/sec.

Table 4. Mining Leachate Chemistry Estimation

	Leachate Code	L1	L2	L3	L4	L5
	Leachate Type	P-GYP (field)	P-GYP (synthetic)	Copper (synthetic)	Copper (synthetic)	Copper (field)
Parameter	Units					
Electrical Conductivity	μS/cm	24,500	171,000	71,000	56,600	45,200
pH	-	1.81	0.5	1.00	1.36	1.96
[I] (mol/L)] =	(mol/L)	0.27	1.52	1.99	2.00	5.11
RMD =	$M^{1/2}$	0.83	0.53	0.21	0.31	0.03
Na^+	(mol/L)	9.3E-02	7.5E-02	1.1E-01	1.2E-01	2.3E-02
Al^{+3}	(mol/L)	1.5E-03	1.4E-03	9.9E-02	5.8E-02	3.8E-01
K^+	(mol/L)	8.93E-03	7.2E-03	2.0E-02	2.2E-02	3.1E-03
Mg^{2+}	(mol/L)	9.04E-03	1.8E-02	2.1E-01	2.2E-01	3.9E-01
Mn^{2+}	(mol/L)	3.3E-05	1.8E-05	4.0E-02	3.6E-02	3.4E-02
Ca^{2+}	(mol/L)	1.8E-02	5.3E-03	1.5E-02	1.7E-02	1.4E-02
Cu^{2+}	(mol/L)	-	-	2.0E-03	2.2E-02	9.8E-03
$PO4^{-3}$	(mol/L)	2.1E-02	6.5E-03	2.4E-02	1.2E-02	1.5E-02
$SO4^{-2}$	(mol/L)	6.4E-03	9.3E-02	4.0E-01	3.9E-01	1.1
Cl^-	(mol/L)	5.5E-02	4.2E-01	9.0E-02	4.3E-01	3.5E-1

Fe^{+3}	(mol/L)	6.2E-04	5.4E-04	-	-	6.1E-02
Zn^{2+}	(mol/L)	1.2E-05	4.3E-06	-	-	6.1E-02
Boron	(mol/L)	1.4E-04	-	-	-	5.8E-04
Cd2+	(mol/L)	4.6E-07	-	-	-	2.2E-03
Pb2+	(mol/L)	2.2E-07	-	-	-	1.7E-05
As^{3+}	(mol/L)	2.9E-05	-	-	-	7.4E-04
Hg^{+2}	(mol/L)	2.7E-08	-	-	-	4.0E-04
Cr^{3+}	(mol/L)	1.2E-05	-	-	-	4.3E-04
Ni^{2+}	(mol/L)	4.4E-06	-	-	-	4.0E-03

Table 5. Hydraulic Conductivity Testing in Various Mining Leachates

Leachate Code	Leachate Type	PMG Sample ID	Effective Stress (kPa)	Pre-Test Moisture Content (%)	Hydraulic Conductivity (cm/sec)	Running time (hours)	Pore Volume
L1	P-GYP	PMG-A3	34.5	27.8	5.7E-10	17,020	14.8
L1	P-GYP	PMG-A4	34.5	19.8	1.4E-09	1,130	2.1
L2	P-GYP	PMG-A3	34.5	27.7	1.3E-08		19.3
L2	P-GYP	PMG-A4	34.5	28.0	8.2E-10	18,049	37.4
L2	P-GYP	PMG-A4	34.5	20.5	6.7E-09		17.4
L2	P-GYP	PMG-A4	34.5	34.0	1.9E-07	34	14.6
L2	P-GYP	PMG-A5	34.5	36.5	1.7E-09	3,401	10.6
L3	Copper	PMG-A2	34.5	19.9	1.9E-08	3,085	86.2
L3	Copper	PMG-A3	34.5	19.8	2.7E-07	66	38.6
L3	Copper	PMG-A4	34.5	19.7	2.5E-08	2,093	44.3
L3	Copper	PMG-A5	34.5	36.0	5.1E-09	8,674	52.5
L4	Copper	PMG-A4	34.5	13.5	3.2E-09	4,488	11.9
L4	Copper	PMG-A4	34.5	17.0	4.7E-09	8,186	41.7
L4	Copper	PMG-A4	34.5	17.5	6.4E-09	10,065	39.8
L4	Copper	PMG-A4	34.5	27.6	7.3E-09	4,623	18.5
L5	Copper	PMG-A4	34.5	7.3	3.5E-07	24	15.0
L5	Copper	PMG-A4	34.5	7.3	9.9E-07	4	7.5
L5	Copper	PMG-A4	34.5	7.3	4.0E-06	2	6.7
L5	Copper	PMG-A4	103.4	25.1	1.7E-09	6,352	35.6
L5	Copper	PMG-A5	34.5	Not measured	3.4E-10	331	0.2
L5	Copper	PMG-A5	34.5	3.8	4.9E-09	1,450	16.1
L5	Copper	PMG-A5	34.5	5.6	8.2E-09	2,072	14.3
L5	Copper	PMG-A5	103.4	5.6	2.0E-10	167	0.0
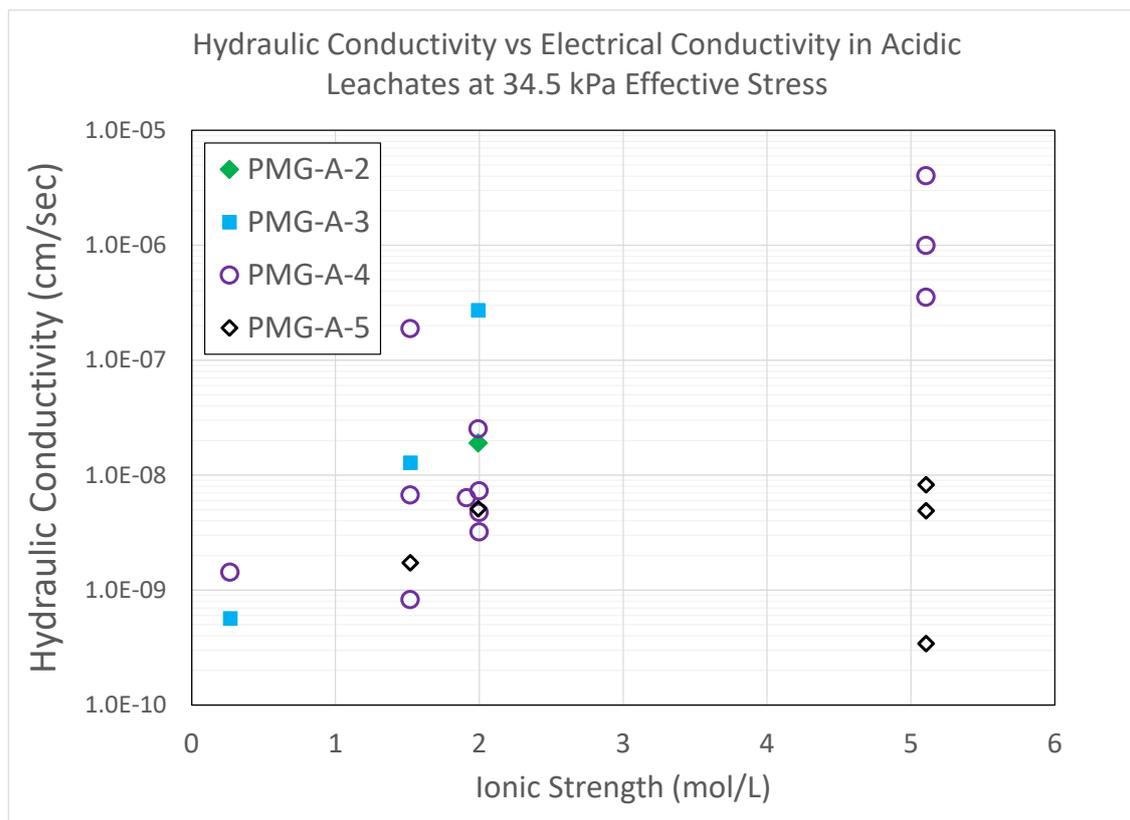
Figure 6. Hydraulic conductivity as a function of ionic strength of the PMG-A systems.

Hydraulic conductivity testing against a synthetic copper leachate was performed after the conclusion of the 0.01M $CaCl_2$ perms. As described earlier, the samples were subjected to 20 ion exchange cycles and were tested for hydraulic conductivity against the 0.01M $CaCl_2$ solution. The samples were allowed to reach 15 pore volumes of flow in the 0.01M $CaCl_2$ solution. After this, the leachate was subsequently switched to the L5 copper solution and the effective stress was increased from 35 kPa to 200 kPa simulating the stresses associated with some heap leach applications. Shown in Table 6 are the hydraulic conductivity results in both the original 0.01M $CaCl_2$ leachate (after 15 PVF) and after transitioning to the L5 leachate. The hydraulic conductivity results in the acidic leachate ranged from $1.1x10^{-9}$ cm/sec to $6.4x10^{-10}$ cm/sec. The performance improved slightly with higher polymer loadings. These results indicate how small levels of this particular polymer treat can allow for ion exchange resistance and low k against aggressive mining leachates.

Table 6. Sequential perm testing results for

ID	LOI (%)	Permeant #1	Effective Stress (kPa)	PVF	k* (cm/sec)	Permeant #2	Effective Stress (kPa)	k** (cm/sec)	PVF
PMG-A1	3.8	0.01 M $CaCl_2$	35	16	2.4E-08	L5	200	1.1E-09	5.2

PMG-A2	5.7	0.01 M CaCl$_2$	35	16	1.1E-08	L5	200	7.6E-10	2.2
PMG-A3	6.7	0.01 M CaCl$_2$	35	15	8.5E-09	L5	200	6.4E-10	1.1
PMG-A4	9.2	0.01 M CaCl$_2$	35	15	4.3E-09	L5	200	6.5E-10	0.4
* GCL subjected to 20 wet/dry cycles prior to testing in 0.01 M CaCl2 at 35 kPa effective stress									
** System transitioned to acidic leachate with 200 kPa effective stress after testing with CaCl$_2$									

CONCLUSION

This work represents a study into the design parameters of PMG systems that influence the resistance towards ion exchange and performance in acidic leachates. For ion exchange studies, approximately 20 wet/dry cycles were needed to reach an ion exchange equilibrium. The free swell and fluid loss values of the polymer/bentonite mixtures were good predictors of hydraulic performance in low RMD leachates. Higher polymer loading resulted in more resistance to the effects of ion exchange. The systems showed good retention of polymer despite hydration in relatively unconfined scenarios. The PMG systems were also tested for hydraulic performance against a range of low pH mining leachates. The systems showed a predictable relationship between hydraulic conductivity and ionic strength. PMGs with higher polymer loading exhibited a less drastic change in hydraulic conductivity as the ionic strength increased. These new PMG materials also showed low hydraulic conductivity against acidic leachates even after complete ion exchange with calcium.

REFERENCES

Benson, C., and Meer, S. (2009). Relative Abundance of Monovalent and Divalent Cations and the Impact of Desiccation on Geosynthetic Clay Liners, J. Geotech. Geoenviron. Eng, ASCE,135(3): 349–358.

Scalia, J. and Benson, C. H. (2011). Hydraulic Conductivity of Geosynthetic Clay Liners Exhumed from Landfill Final Covers with Composite Barriers, *J. Geotech. Geoenviron. Eng*, ASCE, 137(1): 1-13.

Goldenberg, M. and Reddy, K. (2016). Evaluation of Prototype Geosynthetic Clay Liners in Landfill Cover Applications. Proceedings of Geo-Chicago 2016: Sustainability and Resiliency in Geotechnical Engineering, Chicago, IL, ASCE: 398-407.

Donovan M. S., Valorio R. S. and Gebka B. (2016). Chemical Compatibility of Polymer Modified GCLs in Coal Combustion Residual Leachates. GeoAmericas 2016 Proceedings: Vol 1, Miami Beach, FL: 1685

Donovan M. S., Valorio R. S. and Gebka B. (2016). Polymer enhanced geosynthetic clay liners for extreme leachate chemistries. Proceedings of EuroGeo6, Ljubljana, Slovenia.

ASTM D 5890. Standard Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA.

ASTM D 5891. Standard Test Method for Fluid Loss of Clay Component of Geosynthetic Clay Liners, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA.

ASTM D 6766. Standard Test Method for Evaluation of Hydraulic Properties of Geosynthetic Clay Liners Permeated with Potentially Incompatible Aqueous Solutions, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA.