Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

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https://doi.org/10.53243/ICEG2023-281

Effects of Florida Groundwater Chemistry on the Pre-Hydration and Hydraulic Performance of Commercially Available Geosynthetic Clay Liners (GCLs).

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ABSTRACT

Four GCLs were used in this study. Two conventional bentonite (CB): coarse grained (C-GCL) and fine-grained (F-GCL) and two polymer modified bentonite (PMB) with 1.6% polymer (C- GCL-1.6) and with 3.2% polymer (C-GCL-3.2). C-GCL achieved higher water contents than F-GCL when hydrated with low ionic strength groundwater (GWL) and high ionic strength groundwater (GWH). The achieved water content increased as the polymer loading of the GCL increase. C-GCL-1.6 had a higher water content than C-GCL. However, C-GCL-3.2 had a higher water content than C-GCL-1.6.

The hydraulic conductivity of GCLs increased as the polymer loading decreased. F-GCL had lower hydraulic conductivity that C-GCL. C-GCL-3.2 had a lower hydraulic conductivity than C-GCL-1.6 which has a lower hydraulic conductivity than C-GCL. The hydraulic conductivity of both CB and PMB GCLs increased as the ionic strength of the hydrating solution increased. GCLs hydrated with GWL before permeating with municipal solid waste, co-disposal and ash monofil leachates showed lower hydraulic conductivity than the GCLs hydrated with GWH before hydraulic conductivity tests.

Keywords: bentonite, groundwater, hydraulic performance, leachate, polymer-modified GCL, pre-hydration.

1 INTRODUCTION

Geosynthetic clay liners (GCLs) can be an adequate substitute for compacted clay liners in cover and composite bottom liner landfill applications. GCLs are used as single liners in canals, ponds, and protective barriers in transportation facilities (Bouazza,2002). Unlike compacted clay liners which are at least 150 mm thick, GCLs are much thinner. The thickness of a GCL is between 5 – 10 mm (Acikel et al., 2018; Bouazza, 2002; Wireko et al., 2020 and Wireko & Abichou, 2021). GCLs are manufactured in large rolls. The bentonite sandwiched between two geotextiles, or a geotextile and a geomembrane, are bonded by adhesives, stitch bonding, or needle punching (Koerner et al., 2012; Bouazza, 2002; Bouazza et al., 2017 and Wireko et al., 2020). GCLs can comprise either granular or powdered bentonite (Shackleford et al., 2000).

The hydraulic conductivity of a GCL is governed by the swelling capacity of the montmorillonite component of the bentonite (Norrish, 1954). Hydrating bentonite with a dilute solution result in a layer of Na^+ ions and water molecules around individual montmorillonite particles known as the diffuse double layer (DDL) (McBride, 1994). The DDL comprises two distinct layers, the fixed inner layer known as the Stern layer, comprising hydrated cations and some water molecules bound to the montmorillonite surface, and the diffuse outer layer or Guoy layer comprising hydrated cations and water molecules that balance the electrostatic charge of the montmorillonite mineral (Mitchell & Soga, 2005). Formation of the diffuse double layer creates a tortuous path for the permeant solution by reducing the number of conductive pores and pore sizes (Olphen, 1963). Hydraulic conductivity as low as $1.0X10^{-10}$ m/s were reported for GCLs when hydrating solution is dilute (Shackleford et al., 2000; Jo et al., 2001). Sodium bentonite GCLs lose their effectiveness as a hydraulic barrier when in contact with high ionic strength

chemical solutions. The high concentration of cations, especially divalent such as Ca^{2+} hampers osmotic swelling resulting in increased hydraulic conductivity (Jo et al., 2005).

GCLs placed in the field are assumed to sufficiently hydrate to water contents that facilitate low hydraulic conductivity. Active hydration involves directly wetting the GCL after installation, whereas passive hydration is wetting from the subsoil. Hydration after installation but before the GCL encounters the contaminant liquid is important (Shackleford et al., 2000; Rayhani et al., 2011; Anderson et al., 2012 & Bouazza et al., 2017). Passive hydration is more critical for installation. GCLs are covered immediately after installation with an impervious geomembrane. Before encountering waste in a landfill, the extent of hydration is generally unknown (Anderson et al., 2012 & Bouazza et al., 2017). Although GCLs can hydrate passively, only limited studies have dealt with hydration of GCLs from the subgrade.

Coastal regions such as South Florida are prone to saltwater intrusion due to the inward movement of saline water attributed to rising sea levels (Langevin, 2003). The water table in Florida is typically close to the land surface (Sun et al., 2000). Therefore, the bottom liner systems of landfills built in low-lying areas may be constructed at or below the water table. Hydration of GCLs by saline groundwater may affect the hydraulic performance of GCLs. Thus, the objective of this study is to simulate GCLs hydrated by groundwater in the underlying soil.

2. MATERIALS and METHODS

2.1. Geosynthetic clay liners

Four commercially available GCLs were used in the study. Two of the GCLs contained granular sodium bentonite; a coarse-grained (C-GCL) and a finer-grained (F-GCL). The other two GCLs were coarse-grained polymer-modified GCLs with 1.6% polymer (C-GCL-1.6) and 3.2% polymer (C-GCL-3.2) loading. The specific polymer used in commercially available GCLs is proprietary and is not known by the researcher or clients. The polymer(s) used in the polymer-modified GCLs can be classified as linear polymer based on the swelling characteristics of the bentonite extracted from the polymer-modified GCLs (Wireko et al., 2020) and (Wireko & Abichou, 2021). Linear polymers are water-soluble and form a viscous hydrogel when hydrated with water (Billmeyer, 1984; Rivas et al., 2018). Table 1 lists the GCL properties. The granule-size distributions of bentonite extracted from the GCLs was obtained through mechanical sieve analysis. Figure 1 shows the grain size distribution of the GCLs used in this study.

Table 1: *Commercial GCL properties used for this study*

GCL Property	Conventional		Polymer Modified	
Designation	C-GCL	F-GCL	C-GCL-1.6	C-GCL-3.2
Bentonite Type	Coarse	Fine	Coarse	Coarse
Upper Textile	NW	NW	NW	NW
Carrier Textile	NW	SNW	NW	NW
Reinforcement	NP	NP	NP	NP
Tensile strength (kN/m)	8.8	8.7	8.8	8.8
Peel Strength (kN/m)	0.61	0.61	0.61	0.61
Mass per unit area (kg/m^2)	5.1	4.3	4.8	5.5
Initial gravimetric water content (%)	17.5	12.4	19.3	17.5
Polymer Loading (%)	0	0	1.6	3.2

NW =nonwoven, SNW = Scrim nonwoven, NP = needle punch

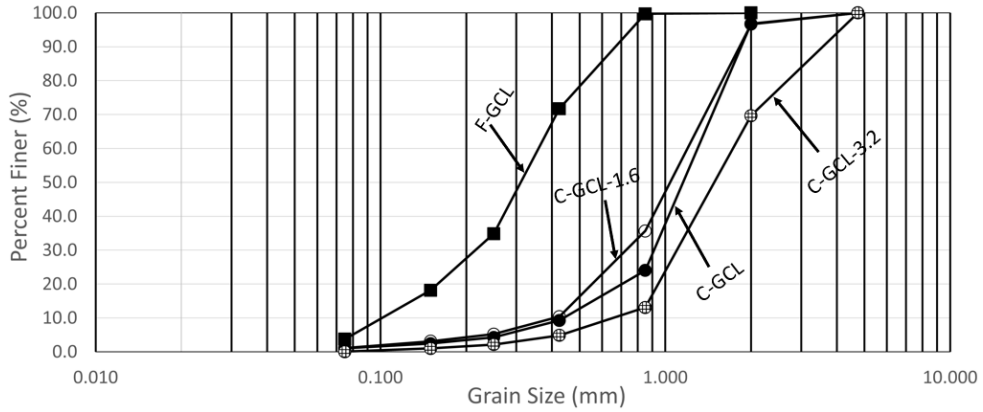


Figure 1: *Grain size distribution of bentonite extracted from GCLs*

2.2. Inorganic salt solutions representing Florida groundwater chemistry

The first extensive review of Florida groundwater geochemistry was reported by Berndt & Katz, (1992). Florida Water Management Districts and the Florida Department of Environmental Protection (FDEP) have collected subsequent groundwater data. Calcium bicarbonate is the primary compound in Florida groundwater at 53%, while sodium chloride accounts for approximately 5% of the salt in groundwater (Reese & Cunningham, 2000; Berdnt & Katz, 1992). Data from Berdnt & Katz, (1992) were used to determine the ionic strengths and ratio of monovalent to divalent (RMD) cations of Florida groundwater chemistry. Inorganic salt solutions simulating groundwater chemistries representing the two extremes of ionic strengths and RMD of Florida groundwater (Benson & Meer, 2009). High ionic strength groundwater (GWH) is representative of groundwater with high ionic strength and high RMD. Low ionic strength groundwater (GWL) represents groundwater with low ionic strength and RMD in Florida (Table 2).

Table 2: *Chemistry of synthetic Florida groundwater*

Hydrating Groundwater	Na^+ (mM)	Ca^{2+} (mM)	Cl^- (mM)	Measured EC (mS/cm)	Measured pH	I (mM)	RMD ($M^{0.5}$)
GWH	35.42	4.63	62.79	13.40	6.70	58.37	0.52
GWL	0.79	2.73	6.03	2.54	6.40	8.87	0.02

EC = electrical conductivity, I = ionic strength, RMD = ratio of monovalent to divalent cations, GWH = High ionic strength groundwater, GWL= low ionic strength groundwater

2.3. Inorganic salt solutions simulating landfill leachates in Florida

Hydraulic conductivity and index tests were performed using synthetic leachates representative of municipal solid waste (MSW) landfills and landfills where MSW incineration (MSW-I) ash is either mono-filled or co-disposed with regular MSW. The chemical properties of the synthetic leachates are summarized in Table 3. The chemical compositions of the synthetic leachates were determined based on the compositions of real leachates collected from MSW, MSW-I ash monofil (AM), and co-disposal (CD) landfills in Florida (Li et al., 2019). The composition of synthetic leachates was based on the average salt concentrations of the overall data for MSW, AM, or CD landfills. For simplicity, K^+ and Mg^{2+} salts were not included in this study. Jo et al, (2001) and Kolstad et al, (2004b) showed that different cation species with the same valence have a similar impact on the swelling and hydraulic conductivity of GCLs over a pH 2–10. Leachates were prepared by dissolving both reagent grade powdered NaCl (representative of all monovalent salts) and $CaCl_2{\cdot}2H_2O$ (representative of all divalent salts) in deionized (DI) water.

Table 3: *Chemistry of synthetic leachates*

Representative leachate	Na^+ (mM)	Ca^{2+} (mM)	Cl^- (mM)	Measured EC (mS/cm)	Measured pH	I (mM)	RMD ($M^{0.5}$)
MSW	45.26	5.45	79.40	16.40	6.80	73.23	0.61
CD	137.76	21.81	250.56	49.00	6.10	237.78	0.93

AM	216.87	42.25	408.98	69.00	6.00	397.43	1.06

MSW = Municipal solid waste, CD = Co-disposal, AM = Ash monofill

2.4. GCL hydration

Cylindrical samples of 101.6 mm diameter were cut from GCL rolls. To prevent loss of bentonite, DI water was sprayed at the edges. Specimens were labelled with the respective hydrating groundwater. GCL thickness was measured at four equal quadrants and averaged. The initial mass of each specimen was measured and recorded. Specimens were loaded into flexible wall permeameters at a cell pressure of 34 kPa. The permeameter cell was connected to a custom-made flat board, which enabled the monitoring of the water intake of each GCL (Figure 2). The flat board, which consisted of rigid tubes containing the hydrating solution, was mounted at the same elevation as the GCL specimen in the permeameter to simulate hydration of the GCL at zero hydraulic gradient. The GCL was hydrated with synthetic groundwater (GWL or GWH) for at least seven days to simulate the GCL being installed in a cell constructed at or slightly below the groundwater table. While hydrating, one of the effluent/output valves on the permeameter remains opened to allow air to escape and avoid air pressure build-up. The volume of water absorbed by the GCL was recorded, and water content calculated.



Figure 2: *Illustrating the height of hydrating GCL and hydrating board*

2.5. Hydraulic conductivity testing

After hydration, the GCLs were permeated with one of three synthetic leachates, namely MSW, CD or AM using the falling headwater-constant tailwater method in ASTM D6766. Conventional GCLs were permeated to at least two pore volumes. Polymer-modified GCLs were permeated for at least 10 pore volumes, even if chemical and volume equilibria criteria were satisfied before 10 pore volumes of flow. Polymer-modified GCLs with hydraulic conductivity higher than the prescribed value of 1.0×10^{-9} m/s required for landfill applications were terminated once chemical and volume equilibria were reached (Jo et al., 2005). The GCLs were permeated using a waterhead pressure difference of 14 kPa with cell pressure of 34 kPa, which resulted in an average effective stress of 20 kPa and an average hydraulic gradient ranging from 120-200 (depending on the bulk thickness of the GCL). The initial thickness of the GCL specimens ranged between 7 and 10 mm. High hydraulic gradients (ranging from 50 up to 2800) are frequently used in hydraulic conductivity testing of GCLs to shorten the test duration (Petrov & Rowe, 1997; Ruhl & Daniel, 1997; Shackelford et al., 2000; Shackelford et al., 2010; Chen et al., 2018; Tian et al., 2019). After permeation, the specimen wet mass and final average thickness were measured and recorded immediately. The specimens were dried in an oven at 110˚ C for 24 hours and then dry mass was recorded.

2.6. Swell index (SI) testing

The swell index (SI) or free swell test (ASTM D5890) is commonly used to assess how the permeant solution can affect the volume change (swelling) of bentonite in GCLs during permeation with a potentially incompatible liquid. Several studies have shown that a correlation exists between the swelling and hydraulic conductivity of both conventional and modified bentonites (Jo et al., 2001; Jo et al., 2004; Kolstad et al., 2004b; Olsta et al., 2004; Lee et al., 2005; Di Emidio et al., 2008; Katsumi et al., 2008; Guyonnet et al., 2009; Scalia et al., 2014, 2018; Wireko et al., 2020). A strong correlation between the SI and hydraulic conductivity of polymer-modified bentonite (PMB) GCLs was reported by Wireko et al., (2020).

In this study, comparative SI tests were performed on bentonite extracted from the conventional sodium bentonite (CB) and PMB GCLs to assess the effect of the polymer on bentonite swelling. The SI tests on the bentonite for CB F-GCL and C-GCL were performed as per ASTM D5890 (i.e., bentonite was crushed and sieved until 100% passed the U.S. No. 100 sieve and at least 65% passed the U.S. No. 200 sieve). First, 90 mL of the hydrating liquid was poured into a 100 mL graduated cylinder. Two grams of the oven-dried powdered bentonite specimen of F-GCL and C-GCL was gently dusted over the surface of the hydrating solution in increments of 0.1 g every 10 minutes until complete. SI of the bentonite extracted from C-GCL-1.6 and C-GCL-3.2 followed a similar procedure to ASTM D5890 except the bentonite was not crushed and sieved before SI testing. The sieving of PMB will result in polymer loss during the process (Wireko et al., 2020). After adding the last portion of bentonite, the graduated cylinder was filled to the 100 mL mark with the same solution, covered, and allowed to sit for 16 h. The volume of the swollen bentonite after 16 h was recorded as the swell index (mL/2g).

3. RESULTS

3.1. Swell index

Figure 3 shows SI of conventional bentonite used in C-GCL and F-GCL. DI water, as expected, provided the highest swell volume. The swelling capacity of bentonite decreased drastically for swell index with groundwater and leachates. The SI with GWL was slightly higher than SI with GWH and synthetic leachates MSW, CD, and AM, due to the low ionic strength of GWL compared to the other solutions. High ionic strength and or divalent cations like calcium are known to retard the swelling of bentonite resulting from the exchange of calcium for sodium cations. High concentrations of monovalent cations such as sodium can also reduce swelling by compressing the DDL.

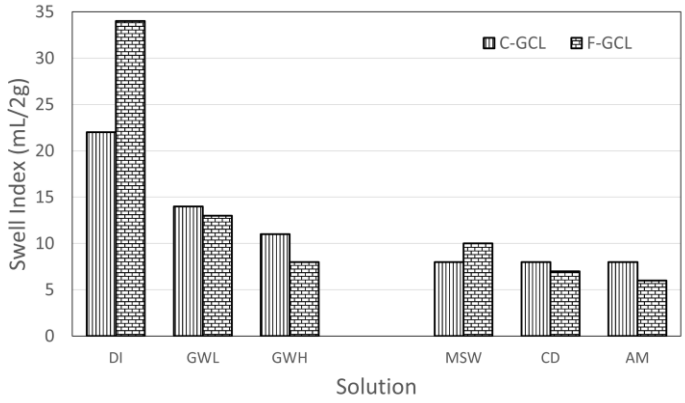


Figure 3: *Swell index (ASTM D5890) of bentonite used in C-GCL and F-GCL*

Adding linear polymer to bentonite increased the swelling capacity of bentonite. In Figure 4 the swelling of conventional (C-GCL) is compared to the swelling of polymer-modified GCLs (C-GCL-1.6 and C-GCL-3.2). Swelling for C-GCL, C-GCL-1.6 and C-GCL-3.2 decreased with the increase of ionic strength. C-GCL-1.6 and C-GCL-3.2 showed superior swelling to C-GCL for SI with DI water, GWL, GWH and MSW. However, C-GCL, C-GCL-1.6 and C-GCL-3.2 have similar swelling with the CD and AM leachates (Figure 4). CD and AM have ionic strengths of 238 mM and 397 mM, respectively. There is no advantage of the polymer at such high ionic strengths. Increasing the polymer loading did not cause an increase in the swelling of the bentonite, suggesting that the additional polymer content is too low to cause a significant difference in swelling.

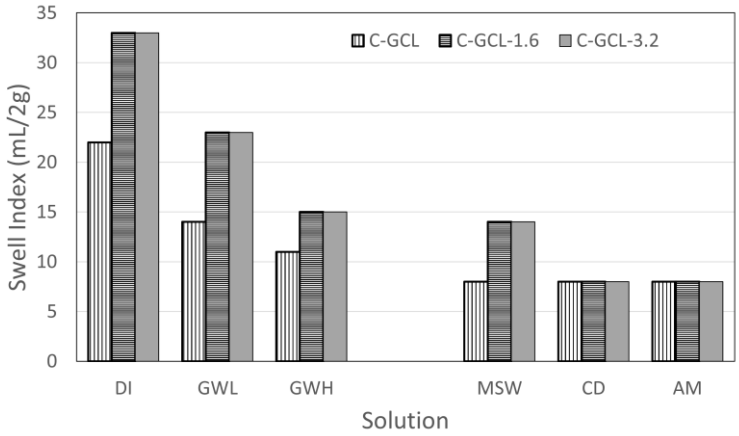


Figure 4: *The effect of polymer inclusion on SI*

3.2. Water Content

3.2.1. Effect of grain size on water content

Figure 5 indicates that C-GCL reached higher water contents than F-GCL during hydration with GWL and GWH. The hydration of a GCL is dependent on the form of the bentonite, whether fine or coarse-grained bentonite (Shackleford et al., 2000; Vangpaisal & Bouazza, 2004; Bouazza et al., 2017). Studies by Rayhani et al. (2011) and Anderson et al. (2012) showed similar trend of water content between coarse-grained and fine-grained CB GCLs.

The chemistry of the hydrating liquid affected the water contents of both C-GCL and F-GCL, as both CB GCLs had lower water contents when hydrated with GWH relative to GWL.

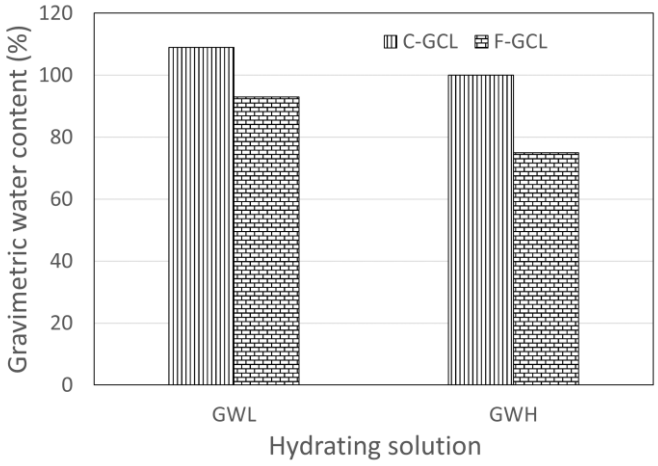


Figure 5: *Effect of grainsize on gravimetric water content*

Absorption and adsorption of water on bentonite in an aqueous solution are controlled by the ability of montmorillonite to interact with water molecules. The presence of cations, especially divalent cations in solution promote charge screening and reduce the interaction of water with montmorillonite causing the DDL to shrink (Slade & Quirk, 1991; Ruedrich et al., 2011). Divalent or multivalent cations such as Ca^{2+} and Mg^{2+} are said to restrict crystalline swelling to an upper limit of 1.9 nm compared to 2.2 nm observed for monovalent cations like Na^{+} and Li^{+} (Theng, 2012). GWH has a higher ionic strength and more Ca^{2+} than GWL. The increased gravimetric water contents observed for GWL relative to GWH indicates that less interaction of the montmorillonite surface with water molecules occurred when GCLs were hydrated

with GWH. Ca^{2+} is more detrimental to the DDL than Na^{+} and other monovalent cations. The negative charges on the external surfaces and the net positive charges in solution adjacent to external surfaces form the electric diffused double layers (Laird, 2006).

C-GCL achieved higher water contents than F-GCL for the same hydrating solution because C-GCL has large macropores that acts as an easy pathway for the hydrating solution. The existence of macropores in C-GCL make it possible for water not related to the wetting of the bentonite to occupy voids. On the other hand, F-GCL with finer bentonite is more compact than C-GCL. The hydration of fine-grained bentonite is much slower than for C-GCL and there are no large pores in fine grained bentonite for water to occupy. In this study, C-GCL achieved the maximum achievable water content. The finer-grained F-GCL was still hydrating at termination.

3.2.2. Effect of polymer inclusion on water content

The inclusion of linear polymer in conventional bentonite in GCLs increases the water content of the GCL, the linear polymers used in commercial GCLs are hydrophilic (De Camillis et al., 2014). Figure 6 shows the gravimetric water contents of C-GCL, C-GCL-1.6 and C-GCL-3.2 hydrated with GWL and GWH. PMB C-GCL-1.6 and C-GCL-3.2 achieved higher water contents than C-GCL for both GWL and GWH. The presence of hydrophilic functional groups like hydroxyl, carboxyl, and sulfonate groups tend to readily absorb water (Hatakeyama & Hatakeyama, 1998; Kadajji & Betageri, 2011). Adding hydrophilic linear polymer to soil increases the water retained by 65% (Chen et al., 2016). C-GCL, C-GCL-1.6 and C-GCL-3.2 hydrated with GWH achieved lower water contents relative to a similar GCL hydrated with GWL. Ionic strength and cation valence affect the water adsorption of polymers (Abraham et al., 2001; Seantier et al., 2009; Al-Hashmi et al., 2012). The greater polymer content in C-GCL-3.2 provides more active sites for water- polymer interact via hydrogen bonding (Di Emildo, 2010; De Camillis et al., 2014).
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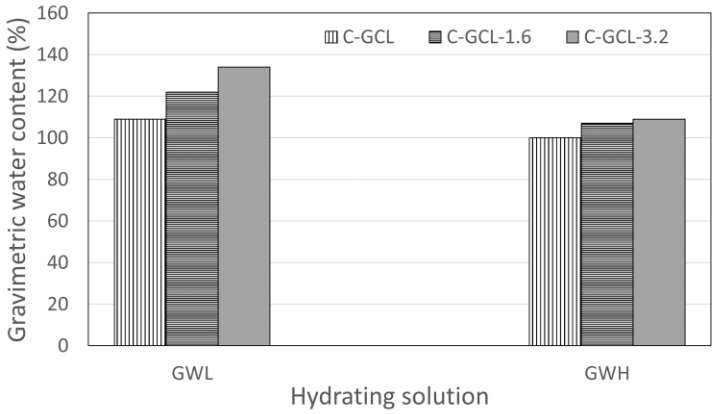


Figure 6: *Effect of polymer inclusion gravimetric water content*

3.3. Hydraulic conductivity

3.3.1. Effect of grain size on hydraulic conductivity

Figure 7 illustrates the hydraulic conductivities of C-GCL and F-GCL. The bars labelled MSW, CD, and AM are for GCLs exposed to only leachates. The bars indicating GWL or GWH before MSW, CD and AM leachates are GCLs hydrated with GWL or GWH before leachate exposure.

F-GCL showed lower hydraulic conductivities than C-GCL in Figure 7. Yadav & Tadikonda, (2022) reported lower hydraulic conductivity of fine-grained bentonite compared to coarse-grained bentonite. Low hydraulic conductivity of F-GCL is attributed to the high specific surface area of finer-grained bentonite exposed to the hydrating solution relative to coarser-grained C-GCL (Vangpaisal & Bouazza, 2004). In water, coarse grained bentonite swells and disintegrates into individual particles due to the formation of the DDL (Lee & Shackleford, 2005). Coarser-grained GCL hydrated with water achieve low hydraulic conductivity (Rowe & Li, 2020; Li & Rowe, 2020; Yadav & Tadikonda, 2022). However,

coarser-grained bentonite hydrated and permeated with cation rich solutions reduces the thickness of the DDL, and the resulting macropores in the bentonite matrix causes high hydraulic conductivity (Acikel et al., 2018).

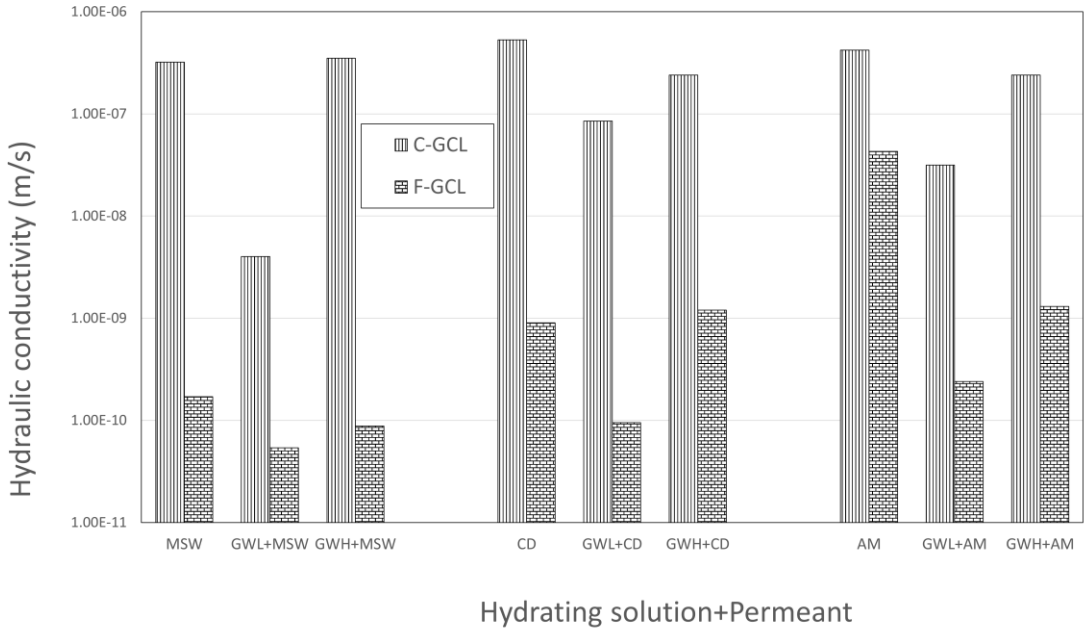


Figure 7: *Effect of grain size on hydraulic conductivity*

Pre-hydration of F-GCL with GWL and GWH before permeation with MSW helped F-GCL to retain low hydraulic conductivities (Figure 7). Pre-hydration of C-GCL with GWL lowered the hydraulic conductivity with MSW leachate. Permeating C-GCL with MSW alone resulted in a similar hydraulic conductivity of C-GCL hydrated with GWH and then permeated with MSW. GWH and MSW have a similar chemistry. When C-GCL is hydrated with GWH, the DDL is suppressed by Na^{+} and Ca^{2+} cations (Bharat et al., 2019). F-GCL is compatible with the MSW leachate for landfill applications.

Hydrating F-GCL and C-GCL with GWL before permeating with CD resulted in lower hydraulic conductivities relative to F-GCL and C-GCL permeated with CD alone. Hydrating F-GCL and C-GCL with GWH did not significantly benefit the hydraulic conductivity of the GCLs. F-GCL hydrated with GWL and permeated with CD can be considered for landfill applications. F-GCL permeated with CD, has hydraulic conductivity borderline the acceptable hydraulic conductivity and would not be recommended for landfills with CD leachates.

Ash monofil leachate is harsh, with an ionic strength of 397 mM and RMD of 1.06 $M^{0.5}$. Pre-hydration of C-GCL with GWL and GWH before permeation with AM leachate cause a slight reduction in the hydraulic conductivity. Pre-hydration of F-GCL with GWL and GWH significantly reduced the hydraulic conductivity of the GCLs to AM leachate. F-GCL permeated with AM after pre-hydration with GWL had a hydraulic conductivity lower than 1.0×10^{-9} m/s which is typically acceptable for landfill use as a barrier component.

In Figure 7, C-GCL hydrated with GWH and then permeated with CD or AM leachate have similar hydraulic conductivities. F-GCL hydrated with GWH and then permeated with CD and AM also have similar hydraulic conductivities. CD has anionic strength of 238 mM and RMD of 0.93 $M^{0.5}$. AM has an ionic strength of 397 mM and RMD of 1.06 $M^{0.5}$. Although AM is much harsher than CD, the CD has adequate concentration of cations to exhaust the swelling capacity of bentonite. Adding harsher leachate in the form of AM did no further harm. C-GCL has a similar hydraulic conductivity when pre-hydrated with GWH and then permeated with CD and AM leachates. F-GCL also exhibited similar hydraulic conductivity when pre-hydrated with GWH and then permeated with CD and AM leachates.

3.3.2. Effect of polymer inclusion on hydraulic conductivity

Figure 8 shows the hydraulic conductivities of C-GCL, C-GCL-1.6 and C-GCL-3.2. The bars labelled MSW, CD, and AM are for GCLs exposed to only leachates. The bars indicating GWL or GWH before MSW, CD and AM leachates are GCLs hydrated with GWL or GWH before leachate exposure.

Polymer-modified C-GCL-1.6 and C-GCL-3.2 have lower hydraulic conductivities than C-GCL for all hydraulic conductivity tests. Hydrophilic linear polymers improve the hydraulic performance of expansive soils (De Camillis et al., 2014; Wireko & Abichou, 2021). Di Emidio, (2010) and De Camillis et al., (2014) reported that the intercalation of anionic sodium carboxymethyl cellulose (Na-CMC) linear polymer intercalates between montmorillonite interlayers and reduce hydraulic conductivity. Hydration of the polymer in the interlayer spacing leads to increased d spacing, causing increased DDL (Di Emidio, 2010; De Camillis et al., 2014). Tian et al., (2016) studied commercially available polymer modified GCLs with proprietary polymer and hypothesized that the improved hydraulic conductivity of polymer-modified GCLs is due to the clogging of macropores by the viscous polymer gel. During the present work, it was noticed that polymer eluted the GCLs, independent of the permeant solution. Polymer elution was reported for commercially available GCLs (Scalia et al., 2014; Tian et al., 2016; Wireko & Abichou, 2021). (Wireko & Abichou, 2021) proposed the possibility of linear polymers scavenging cations from leachate, to make bentonite swell more.

C-GCL-3.2 has a higher polymer loading than C-GCL-1.6. C-GCL-3.2 has a lower hydraulic conductivity than C-GCL-1.6 for all hydraulic conductivity tests. Lower hydraulic conductivity of C-GCL-3.2 is due to the additional functional group active sites for permeant to interact with. if clogging is the mechanism at play more polymer in the bentonite cause an increase the viscosity, which is beneficial for low hydraulic conductivity (Tian et al., 2016). Increased polymer loading can cause more intercalation of polymer into the montmorillonite interlayer, resulting in lower hydraulic conductivity (Di Emidio, 2010), if intercalation is the mechanism. More polymer in C-GCL-3.2 can cause the trapping of more cations from the hydrating solution making the hydrating solution more dilute as stated by (Wireko & Abichou, 2021). Divalent cations like Ca^{2+} contract polymer chains linear polymers and physical crosslinking or chemical crosslinking of polymer chains (Peng & Wu, 1999). Without knowledge of the specific polymer used in the polymer-modified C-GCL-1.6 and C-GCL 3.2, no claims can be made about the specific mechanism that enhances the hydraulic conductivity of polymer-modified GCLs used in this study.

C-GCL-1.6 and C-GCL-3.2 permeated with MSW meet the required 1.0 x 10^{-9} m/s for landfill applications. C-GCL and C-GCL-1.6 are incompatible with landfills with CD and AM harsh leachates. Pre-hydration of C-GCL-3.2 with GWL and GWH before contact with CD leachate aided the hydraulic performance. C-GCL-3.2 is viable for landfill use with co-disposal leachates.

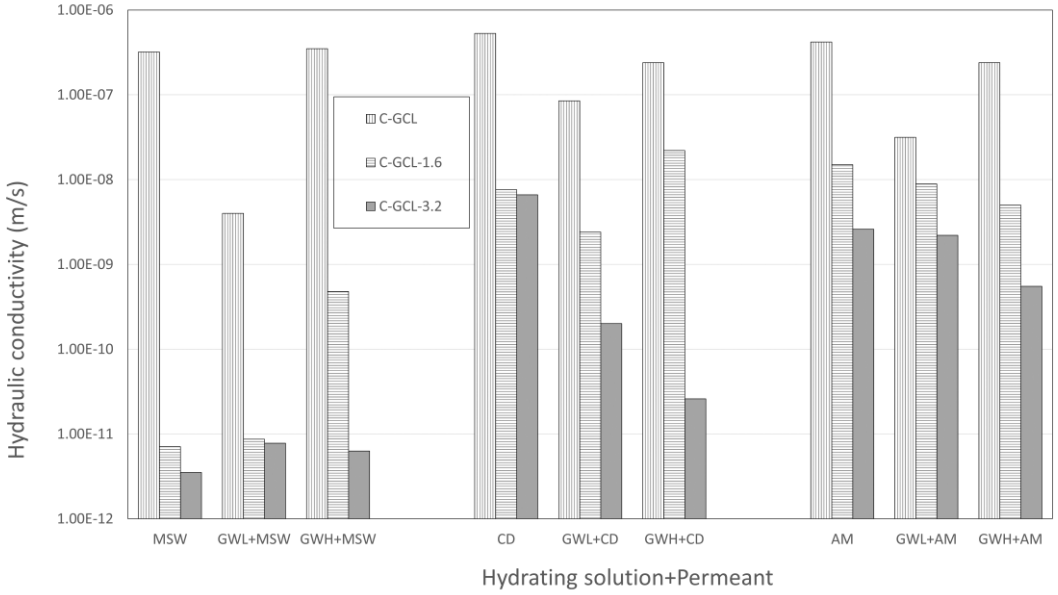


Figure 8: Effect of polymer inclusion on hydraulic conductivity

4. CONCLUSION

The swell index and hydraulic conductivity of conventional and polymer-modified GCLs are affected by the chemistry of the hydrating and permeating solutions. Hydrating all GCLs with GWL resulted in lower hydraulic conductivity than the GCLs hydrated with GWH before permeation with MSW, CD or AM leachates. Hydration of bentonite with a more dilute GWL relative to GWH causes more bentonite swelling.

Higher gravimetric water content is generally considered to be an indication of better hydraulic performance. However, this statement does not consider how the granule size can affect the hydration and swelling of GCLs. Although coarser-grained C-GCL achieved higher gravimetric water content than finer-grained F-GCL, F-GCL exhibited lower hydraulic conductivities than C-GCL. F-GCL with finer-grained bentonite requires minor swelling to block pores. Even if osmotic swelling occurs in C-GCL, the pores are too large to achieve low hydraulic conductivity.

C-GCL achieved lower gravimetric water contents than C-GCL-1.6 and C-GCL-3.2. Polymer addition to bentonite caused an increase in the water content of GCLs because of the high affinity of water-soluble linear polymer for water. The polymer in the bentonite matrix increases the number of active sites for water interaction/absorption. The functional groups in the polymer used for commercially available GCLs are unknown because the specific polymers used are unknown. Increasing the polymer amount in a GCL will further increase active sites via functional groups. C-GCL-3.2 with more polymer in the bentonite matrix achieve higher gravimetric water contents than C-GCL-1.6 with a lower polymer loading. Hydraulic conductivity decreased as the polymer loading increased. C-GCL has a higher hydraulic conductivity than C-GCL-1.6. C-GCL-3.2 with a higher polymer loading than C-GCL-1.6 has a lower hydraulic conductivity than C-GCL-1.6. Authors have theorized that the mechanism at work is clogging, polymer causing increased DDL and scavenging cations from bulk solution, making it more dilute, causing more swelling. With no idea of the specific polymer used in GCLs, no knowledge of the mechanism responsible for the hydraulic improvement can be stated. Controlled studies are needed to ascertain the mechanisms controlling the hydraulic improvement of polymer-modified GCLs. With knowledge of the specific polymer, important information such as the functional groups, degree of polymerization, and possible chemical reaction is known.

5. ACKNOWLEDGEMENT

This material is based on work supported by the Hinkley Center for Solid and Hazardous Waste Management and Environmental Research and Education Foundation (EREF). Any opinions, findings, and conclusions in this material are those of the authors. They do not necessarily reflect the views of the Hinkley Center for Solid and Hazardous Waste Management and EREF.

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