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Advancing the Use of Geosynthetic Clay Liners as Barriers

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ABSTRACT: Geosynthetic clay liners (GCLs) are effective barrier materials for liner and cover systems in waste containment applications. Exposure to non-standard chemical solutions can alter the chemical and mechanical properties of both the bentonite and geotextiles comprising a GCL. Considerable advances in laboratory testing and analysis of GCLs have occurred recently in regard to hydraulic conductivity, the existence and persistence of membrane behavior, and long-term shear strength of GCLs evaluated under stress-controlled conditions. The objective of this paper is to present a synopsis of advances in research related to GCLs that is focused on enhancing knowledge of GCLs used as hydraulic and chemical contaminant barriers.

KEYWORDS: Bentonite, Chemico-osmosis, Containment barrier, Enhanced bentonite, Geosynthetic clay liners, Hydraulic conductivity, Membrane behavior, Polymerized bentonite, Shear strength

1. INTRODUCTION

Geosynthetic clay liners (GCLs) are thin (10±5 mm), factory manufactured (prefabricated), hydraulic barriers (liners) that comprise primarily a processed clay, typically either natural sodium bentonite (Na-bentonite) or sodium-activated calcium bentonite (Na-activated Ca-bentonite), encased or "sandwiched" between two geotextiles or attached to a single polymer membrane (e.g., polyethylene geomembrane or geofilm) and held together by needle-punching, stitching, and/or gluing with an adhesive. The hydraulic resistance of GCLs that do not include a polymer membrane is attributed entirely to the bentonite component of the GCL, which swells in the presence of water to form a tight sealing layer (e.g., Daniel et al. 1997, Rowe 1998, 2005, 2006, 2007, Bouazza 2002, Koerner 2005, Shackelford et al. 2010, Shackelford and Sample-Lord 2014). The manufactured GCL panels, typically on the order of 4.2 to 5.3 m wide and 30 to 61 m long (U.S. EPA 2001), are transported to the site in rolls and installed simply by unrolling and overlapping adjacent GCL panels (~ 0.15 to 0.3 m) to provide a continuous barrier for hydraulic and/or chemical containment. In some cases, a thin bead of dry bentonite (~ 0.4 kg/m) may be required between the overlapped GCL panels to insure a tight seal. The GCL panels also can be readily cut with a sharp blade (e.g., knife) to adapt placement of the GCL panels to irregular patterns or geometries.

Daniel and Gilbert (1996) report that GCLs were first used for waste containment at a hazardous waste landfill in 1986. Since then, GCLs have been used in a wide variety of hydraulic and chemical containment applications, including landfill liners and covers (Du Preez et al. 2012, Ng and Ramsey 2012), surface impoundments (e.g., ponds and lakes, aeration lagoons, fly ash lagoons, and other surface impoundments), canals, mining applications such as tailings impoundments and heap leach pads (Naka et al. 2012), and secondary containment of above-grade fuel storage tanks.

The preference for GCLs relative to other barriers or barrier components, such as compacted clay liners (CCLs) and geomembrane liners (GMLs), has occurred primarily for two reasons (e.g., Koerner and Daniel 1995, Shackelford 2008). First, GCLs generally offer a savings in cost due to easier installation relative to either CCLs or GMLs and an increase in storage capacity relative to that associated with thicker CCLs. Second, GCLs offer several technical advantages relative to CCLs and/or GMLs. The primary technical advantage typically has been the extremely low hydraulic conductivity, *k*, of GCLs when permeated with water or dilute aqueous solutions, which typically is less than about 3.0×10^{-11} m/s (e.g., Daniel et al. 1997, Shackelford et al. 2000, Scalia et al. 2014). Other technical factors favoring the use of GCLs are the greater self-healing capability of the bentonite in GCLs relative to CCLs constructed with typically lower plasticity natural clay soils, and a generally greater ability to withstand relatively large differential settlements compared with CCLs (Shackelford 2008, Scalia et al. 2017). The greater self-healing capability of GCLs allows GCLs to overcome small defects (e.g., puncture holes up to 75 mm in diameter) upon hydration (EPA 2001).

However, for applications where liquids other than water or dilute aqueous solutions are to be contained, such as concentrated brines, organic solvents, and concentrated aqueous solutions of inorganic chemicals, there is concern for incompatibility between the bentonite component of the GCL and the liquid resulting in significant increases in the hydraulic conductivity, *k*, of the GCL. Also, for GCLs placed on sloping surfaces, the inherently low internal and interface shear strength of GCLs remains a concern affecting the use of GCLs in some applications, such as for heap leach pads where several tens of meters of ore are stacked or heaped upon a liner inclined at slope angles as low as a few degrees for the purpose of draining and collecting the pregnant leachate. In addition, several relatively recent advances have been made with respect to the GCL technology, including the use of polymerized bentonites that are able to better resist chemical incompatibility, and the recognition that the bentonite in GCLs can behave as a semipermeable membrane that acts to selectively restrict the migration of dissolved chemical constituents from passage through the GCL.

Accordingly, the purpose of this paper is to present the results of research conducted to advance the use of GCLs as hydraulic and chemical containment barriers. In this regard, the presentation focuses on three key areas, viz., hydraulic conductivity and compatibility of GCLs, the existence and persistence of membrane behavior in GCLs, and long-term shear strength of GCLs under different conditions (e.g., temperature and hydration solution). Behaviors under saturated conditions are described, since saturated conditions generally yield the most conservative (worst case) condition for GCLs, i.e., highest hydraulic conductivity (Shackelford et al. 2000), lowest membrane efficiency (Sample-Lord and Shackelford 2017a), and lowest shear strength (Fox and Stark 2015), and generally are far easier to evaluate.

2. BACKGROUND

2.1 Hydraulic Behaviour

Use of GCLs as hydraulic and chemical containment barriers typically is based on the low *k* (typically < $2\text{-}3 \times 10^{-11}$ m/s) of GCLs to water or dilute aqueous solutions (Daniel et al. 1997, Shackelford et al. 2000, Bouazza 2002, Jo et al. 2004, Kolstad et al. 2004). GCLs that do not include a polymer membrane derive low *k* from the swelling of the bentonite component, which in the presence of water or dilute aqueous solutions swells to form a tight sealing layer. A cross-section of a dry (new) GCL containing sand-sized granules of bentonite is shown in Figure 1a. Upon introduction of water or dilute aqueous solutions, bentonite swells as water is drawn into and around the montmorillonite (clay mineral) platelets that principally comprise bentonite. The swelling of bentonite granules results in the tight sealing layer and low *k* of GCLs used in hydraulic and chemical containment barriers, and is shown in Figure 1b for a GCL hydrated with deionized water.

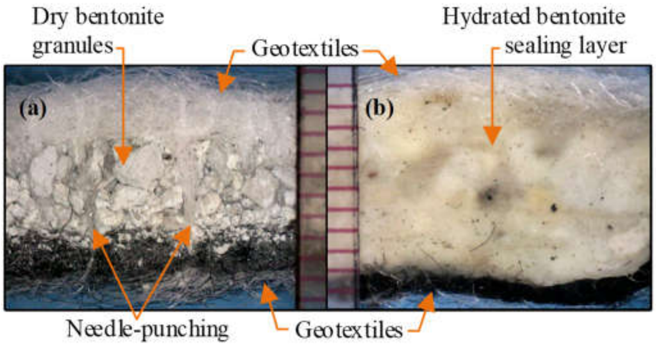

Figure 1 Cross-section photographs of (a) a new needle-punched GCL containing granular bentonite, and (b) the same GCL hydrated with deionized water. Scale in mm

For a GCL to provide low *k*, the bentonite component must form a tight sealing layer. Conditions that reduce bentonite swelling diminish or eliminate the formation of a tight sealing layer, resulting in increases in *k* that reduce or eliminate the functionality of a GCL as a barrier layer. Two conditions reduce the swelling of hydrated bentonite: (i) exchange of multivalent cations (e.g., calcium) for native, monovalent sodium initially occupying the exchanges sites of the clay particles McBride 1994) reduces, but does not eliminate, the sealing layer (Shackelford et al. 2000, Jo et al. 2005, 2006), and (ii) mass action, whereby concentrated aqueous solutions reduce or eliminate the sealing layer (Shackelford et al. 2000, Jo et al. 2004, Lee and Shackelford 2005, Katsumi et al. 2007). Furthermore, two conditions can preclude the formation of a hydrated bentonite sealing layer: (i) hydration with a concentrated aqueous solution (Jo et al. 2001), and (ii) cation exchange followed by desiccation and subsequent rehydration of the exchanged bentonite, since multivalent bentonite such as calcium-bentonite swells substantially less than sodium bentonite (Meer and Benson 2007, Benson and Meer 2009, Scalia and Benson 2011). Thus, GCL *k* is a function of the concentration and composition of permeant solution, bentonite characteristics, and also stress conditions under which permeation occurs (Petrov et al. 1997, Bradshaw and Benson 2014). The effect of the concentration and composition of the hydrating and permeant solutions on GCL *k* are described subsequently, with the goal of understanding general conditions under which GCLs will, or will not, function as effective barriers. Finally, the emerging use of enhanced bentonites engineered to maintain low *k* in concentrated aqueous solutions is described.

2.2 Shear Strength

Geosynthetic clay liners used in barrier applications often are deployed on slopes and, thus, GCLs must have sufficient interface shear strength with respect to adjacent materials and internal shear strength to provide sufficient slope stability (Bouazza 2002, Zornberg et al. 2005, Chen et al. 2011, Fox and Stark 2015). Geosynthetic clay liners deployed on slopes are subjected to long-term states of induced normal and shear stresses (Müller et al. 2008, Zanzinger and Saathoff 2012, Breitenbach and Athanassopoulos 2013) that must be resisted at both the interfaces and internally within the GCL, such that the designed hydraulic and mechanical performance is maintained throughout the lifespan of the GCL.

Fox and Stark (2015) present a detailed summary on the interface and internal shear strength of GCLs. Their summary highlights the development and application of novel displacement-controlled direct shear tests on unreinforced and reinforced GCLs. In addition, Fox and Stark (2015) note that the long-term shear strength of GCLs under sustained stress conditions remains relatively unknown. Long-term shear strength of GCLs is dependent on GCL material characteristics (e.g., geotextiles, bentonite, internal reinforcement, thermal bonding) and site-specific factors (e.g., induced stress, bentonite hydration, hydration fluid chemistry, temperature). Geosynthetic clay liners deployed in barrier applications typically contain dry, granulated bentonite that hydrates when in contact with a hydrated subgrade or infiltrating fluid (e.g., Bradshaw et al. 2013). The initial, internal shear strength of a GCL is dependent of the internal, effective stress friction angle, ϕ', of the dry, granulated bentonite with additional strength reinforcement provided by the needle-punched geosynthetic fibers (Fox and Stark 2015). As the bentonite in the GCL hydrates, there is a reduction in shear strength.

The value of ϕ' for sodium montmorillonite, the predominant clay mineral in bentonite, can be insufficiently low for consideration of the long-term (drained) strength. For example, Mesri and Olson (1970) reported $\phi' \leq 4°$ for sodium bentonite at a confining stress of 70 kPa. However, the exchange of Ca^{2+} for Na^{+} in montmorillonite can increase ϕ' to approximately 10-15°, due to a reduced amount of hydrated water associated with the Ca^{2+} in the diffuse double layers (DDLs) surrounding individual bentonite particles (Mesri and Olson 1970). Although an increase in shear strength due to cation exchange is beneficial for slope stability, the exchange of divalent-for-monovalent cations can increase *k* as previously noted. Thus, cation exchange in bentonite within the GCL has mechanical advantages but hydraulic disadvantages for long-term performance as a barrier material.

Relevant research on stress-controlled direct shear testing of GCLs has included evaluations of test methods (e.g., stress application method), temperature, GCL characteristics, hydration time, applied normal stress, and creep stress ratio. The creep stress ratio (τ_c/τ_p) is defined herein as the applied shear stress during creep (τ_c) divided by the peak shear strength (τ_p) obtained from a displacement-controlled test. A considerable number of these studies (e.g., Siebken et al. 1997, Trauger et al. 1997, Koerner et al. 2001, Zanzinger and Alexiew 2000, 2002) reported no internal GCL failure for a broad range of experimental variables. For example, Müller et al. (2008) performed creep tests under constant shear stress to normal stress ratio on heat-treated (HT) and non-heat-treated (NHT) needle-punched GCLs. Specimens were hydrated in de-ionized water (DW) or tap water (TW) and subjected to temperatures of 20 °C, 50 °C, and 80 °C. Failure was not observed for specimens hydrated in TW; however, failure did occur for some specimens hydrated in DW and tested at an elevated temperature. Also, Zanzinger and Saathoff (2012) and Zanzinger (2016) conducted stress-controlled tests on stitch-bonded and needle-punched GCLs at 80 °C and reported failure for specimens at $\tau_c/\tau_p \geq 0.4$ within a few days to months. They also observed an increase in the time to reach failure with a decrease in the applied shear stress.

These previous studies imply that internal shear failure of GCLs can be achieved in stress-controlled shear tests. However, experimental conditions such as temperature and chemistry of the hydration solution need to be taken into account. Conditions that couple elevated temperature and non-standard hydration solution are relevant to a broad range of waste containment barrier systems. For example, Hornsey et al. (2010) report that the combination of strongly acidic or alkaline mine process waters with elevated temperature represents a critical condition to long-term geosynthetic performance in mining applications. Geosynthetic clay liners used in liner systems for heap-leach facilities can be exposed to a broad range of inorganic chemical solutions that can influence polymer degradation (e.g., Bouazza 2002, Hornsey et al. 2010). Hsuan (2002) reports that the type and abundance of antioxidants in polymer-based geosynthetics are the primary factors controlling resistance against long-term oxidative degradation. Antioxidants in all polymeric geosynthetics are reduced during the lifespan of the geosynthetics, and the rate of antioxidant depletion increases with increasing temperature and/or increasing oxygen concentration (Hsuan 2002). Thus, the potential for enhanced geosynthetic degradation combined with decreasing ϕ' of montmorillonite with increasing confining stress renders the long-term strength performance of GCLs used in mining applications questionable and, therefore, of critical concern. To this extent, innovative experimental methods for conducting stress-controlled direct shear tests on GCLs have been developed to advance the state-of-art and state-of-practice related to mechanical properties of GCLs exposed to elevated temperatures and non-standard hydration solutions.

2.3 Semipermeable Membrane Behaviour

2.3.1 Background

Membrane behavior refers to the ability of porous media to restrict the migration of dissolved chemical species (i.e., solutes) from passage through the medium. For example, manufactured polymer films or membranes are used in desalination plants to sieve dissolved salts (e.g., NaCl) from salt water for the purpose of generating purified water via a process known as reverse osmosis. In this case, the polymer membranes contain numerous holes that are sufficiently small so as to restrict hydrated ions from migrating through the membrane but also sufficiently large to readily allow the passage of the water molecules (H_2O). In the absence of any applied pressure, the water will migrate through the membrane from the lower salt concentration (higher water activity) side of the membrane to higher salt concentration (lower water activity) side of the membrane via a process known as chemico-osmosis (e.g., Mitchell and Soga 2005). Thus, by superimposing an applied pressure to the water on the higher salt concentration side, water is forced to move from the higher salt concentration to the lower salt concentration side via a process known as reverse chemico-osmosis, thereby sieving the hydrated ions from the salt water resulting in purified water on the lower salt concentration side. This mechanism by which solutes are restricted from migrating through a porous membrane in this manner is known as steric hindrance.

Some clays, especially those with particles comprising high swelling clay minerals, such as the sodium smectites (e.g., sodium montmorillonite), also have been shown to exhibit membrane behavior (e.g., Kemper and Rollins 1966, Kemper and Quirk 1972). In this case, solute restriction results when adjacent particles are sufficiently close such that the negative potentials or DDLs associated with the particles overlap, thereby restricting the migration of negatively charged ions, i.e., anions (e.g., Cl^-), within the pore water through the pore space between the particles due to electrostatic repulsion. Because of the requirement for electroneutrality in solution, any associated positively charged ions, i.e., cations (e.g., Na^+), also are restricted from migrating through the pore space.

Unlike the situation with polymer membranes, where the sizes of the openings in the membrane are fixed, the pore spaces between adjacent clay particles can change as a function of both mechanical and physico-chemical processes. For example, mechanical compression of the clay via compaction or consolidation results in a decrease in the void ratio, e, of the clay that correlates with a decrease in pore size and a concomitant decrease in k. Also, for a given pore size, a decrease in the solute concentration of the pore water between adjacent clay particles results in an increase in the extent of influence of the negative surface potentials of the clay particles which, therefore, decreases the solute accessible or free pore space available for solute migration. Thus, both of these factors tend to favor the possibility of membrane behavior. In contrast, an increase in e and/or an increase in the pore-water concentration of solutes results in larger pore openings and a decreased tendency for solute restriction (e.g., Shackelford et al. 2003).

The extent to which a porous medium exhibits semipermeable membrane behavior is quantified in terms of a reflection coefficient designated as σ or a membrane (chemico-osmotic) efficiency coefficient designated as ω. The σ notation and terminology are typical in the science disciplines (e.g., soil science, geological sciences), whereas the ω notation is preferred in the engineering disciplines, because σ commonly is used to designate mechanical stress or electrical conductivity (e.g., Mitchell and Soga 2005). In general, ω (or σ) varies from zero for porous media that exhibit no solute restriction or membrane behavior (e.g., clean sands and gravels) to unity for porous media that restrict all solutes, which is referred to as ideal or perfect membrane behavior (i.e., $0 \leq \omega \leq 1$). However, the pore sizes in clays that exhibit membrane behavior vary, such that some pores generally are solute restrictive whereas others are solute conductive. Thus, for clays that exhibit some membrane behavior, ω tends to vary between zero and 100 % (i.e., $0 < \omega < 1$) and, therefore, these clays are referred to as nonideal or imperfect membranes.

Because bentonites are known to comprise variable percentages of high swelling sodium smectite, bentonite-based engineered barriers such as GCLs also are known to behave as semipermeable membranes (Shackelford 2011, 2012, 2013; Meier and Shackelford 2017). Since membrane behavior results in solute restriction, the existence of membrane behavior in GCLs and other bentonite-based barriers represents a benefit to the use of these barriers for chemical containment, i.e., not only does the bentonite aid in terms of hydraulic containment via a reduction in k, but also the bentonite works to restrict chemical migration through the barrier. For this reason, significant interest in determining the extent and magnitude of membrane behavior in bentonite-based barriers such as GCLs has occurred over the past few decades. Accordingly, some of the more significant findings pertaining to the membrane behavior of GCLs are described subsequently, with the goal of advancing the use of GCLs for chemical containment applications.

2.3.2 Measurement

A method to measure ω for clays based on the use of a rigid-wall cell was developed by Malusis et al. (2001), and this method subsequently was extended for use with a flexible-wall cell (e.g., triaxial cell) by Kang and Shackelford (2009). Both approaches are based on a closed system, whereby expansion of the specimen is prevented from occurring during measurement of ω. However, the possibility of specimen shrinkage during testing exists in the case of the rigid-wall system, resulting in short-circuiting or destruction of membrane behavior, whereas the application of a constant, total confining stress, σ_c, in the case of the flexible-wall cell prevents short circuiting (e.g., Bohnhoff et al. 2014). More recently, a modified rigid-wall cell that included the use of a flexible (polymer) membrane placed between the rigid sidewalls of the cell and the specimen was used to accommodate the potential for specimen shrinkage during testing (Sample-Lord and Shackelford 2014, 2017a,b).

A schematic of the general testing apparatus developed by Malusis et al. (2001) is shown in Figure 2 (also see Kang and Shackelford 2009, and Shackelford 2017). In this system, electrolyte (inorganic) chemical solutions are circulated simultaneously at the same rate across both the top and bottom boundaries of a specimen enclosed within a rigid-wall cell via displacement of the plungers within two syringes (actuators) that are driven by a mechanical (flow-pump) apparatus (not shown). The source concentrations of the salt(s) in top and bottom circulating liquids, C_{ot} and C_{ob}, respectively, are maintained constant and different so as to establish a concentration difference, ΔC ($= C_{ob} - C_{ot}$) across the specimen. Generally, a simple salt solution, typically either KCl or $CaCl_2$, is used for the top circulating liquid (i.e., $C_{ot} > 0$) and DW is used for the bottom circulating liquid (i.e., $C_{ob} = 0$), such that $\Delta C < 0$. Note that ΔC is negative only on the basis of sign convention, because the positive sign convention is from top to bottom of the specimen, or in the direction of diffusion. The plunger displacement rate is sufficiently fast so as to consider the boundary salt concentrations essentially constant, but sufficiently slow so as to not result in the need for too frequent refilling of the syringes with fresh circulating liquids and measurable solute concentrations in the top and bottom circulation outflows (i.e., C_t and C_b in Figure 2). Typically, the plunger displacement rate has corresponded to either a one-day or a two-day circulation cycle. The specimen is saturated (e.g., by permeation with water prior to membrane testing) and contained within a rigid-wall cell, such that volume change (expansion) of the specimen is prevented. Also, the top and bottom circulating systems are maintained within a closed loop, such that volume change within the circulating systems also is prevented. Thus, volume change of the entire system is prevented. However, diffusion of salt ions through the specimen can still occur in response to the established ΔC, i.e., provided there are pores within the specimen that are sufficiently large to accommodate solute migration. In the case where $C_{ot} > C_{ob}$, salt ions in the top circulating liquid will diffuse into and eventually through the specimen, such that the concentrations of these ions in the circulation outflow from top, C_t, will be lower than C_{ot} (i.e., $C_t < C_{ot}$), whereas the concentrations of these ions in the circulation outflow from bottom, C_b, will be higher than C_{ob} (i.e., $C_b > C_{ob}$). Simultaneously, if some of the pores within the specimen are solute restricting such that diffusion through these pores is prevented, then there will be a tendency for chemico-osmotic flow of liquid from the bottom of the specimen to the top of the specimen. However, because there is no space available in the top circulating system for liquid to migrate through the specimen and accumulate, a chemico-osmotic pressure difference, ΔP, will develop across the specimen to counteract the tendency for chemico-osmotic liquid flow. The magnitude of ΔP is measured with a differential pressure transducer, and used to calculate ω based on the following expression (Malusis et al. 2001):

$$\omega = \frac{\Delta P}{\Delta \pi} \qquad (1)$$

where $\Delta\pi$ is the maximum possible chemico-osmotic pressure difference corresponding to ideal membrane behavior ($\omega = 1$) for the imposed ΔC. Thus, ω as given by Eq. 1 represents the extent of solute restriction as represented by ΔP relative to the maximum value of ΔP expected on the basis of complete solute restriction corresponding to ideal membrane behavior as represented by $\Delta\pi$. Thus, when there is no solute restriction, $\Delta P = 0$ such that $\omega = 0$, whereas when there is complete solute restriction, $\Delta P = \Delta\pi$ such that $\omega = 1$. As previously noted, the variability in pore sizes in clays typically results in $0 < \Delta P < \Delta\pi$, such that $0 < \omega < 1$. Since $\Delta\pi$ is a function of ΔC, the values of C_{ot} and C_{ob} can be varied to establish different values of ΔC and, therefore, evaluate the effect of concentration on the measured ω of the specimen. Further details on this method of measuring ω can be found in the aforementioned references.

3. HYDRAULIC CONDUCTIVITY

3.1 Hydraulic Compatibility

The relationship between GCL *k* and concentration of the permeant solution (in terms of ionic strength) is presented in Figure 3 for tests conducted at low effective stress, σ' (16-24 kPa), medium σ' (70-100 kPa), and high σ' (250-520 kPa). All data plotted in Figure 3 are for tests conducted until both hydraulic and chemical equilibrium were achieved based on the following criteria: (1) no systematic trend in *k* over time (per ASTM D5084), (2) at least four consecutive hydraulic conductivity readings within ± 25% of the mean (per ASTM D5084), (3) at least four consecutive outflow-to-inflow ratios within 1.0 ± 0.25 (per ASTM D5084), and (4) establishment of chemical equilibrium [defined as the ratio of electrical conductivity, EC, of the effluent solution relative to that of the influent solution being within 1.0 ± 0.1 (per ASTM D6766)]. Termination criteria 1-3 are typical of *k* tests (Daniel 1994). Termination criteria 4 is critical to assess potential incompatibility of a GCL with a permeant solution (Jo et al. 2005, 2006).

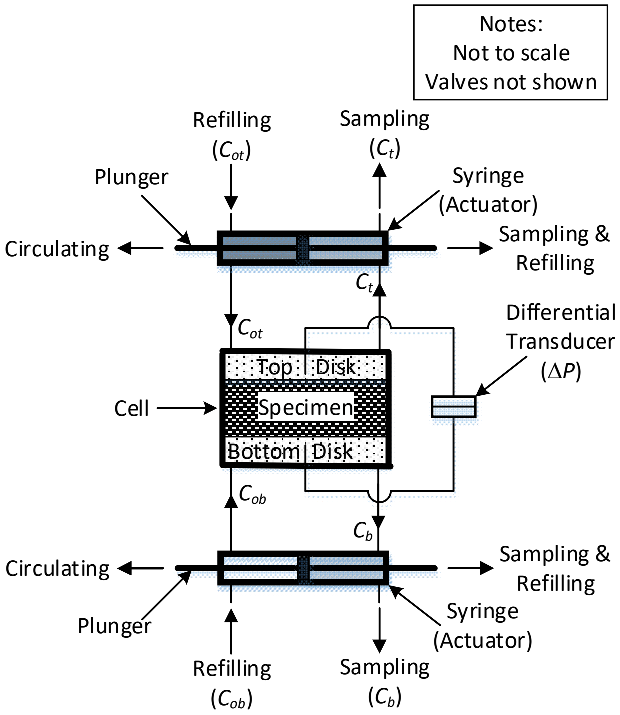

Figure 2 Schematic of closed-system testing approach for measuring semipermeable membrane behavior of clays (modified after Malusis et al. 2001)

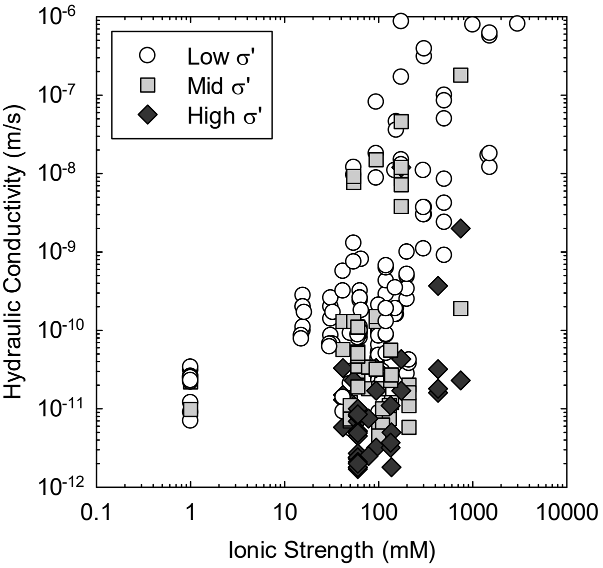

Figure 3 Hydraulic conductivity as a function of the ionic strength of the permeant solution for GCLs permeated at effective stresses between 16-24 kPa (Low σ'), effective stresses between 70-100 kPa (Mid σ'), and effective stresses between 250-520 kPa (High σ'). Data from Jo et al. (2004), Kolstad et al. (2004), Jo et al. (2005), Lee and Shackelford (2005a, 2005b), Lee et al. (2005), Benson et al. (2014), Bradshaw and Benson (2014), Bradshaw et al. (2016). Tests with deionized water are plotted at an ionic strength = 1 mM.

Data are for both prehydrated GCLs, i.e., GCLs initially permeated with water or a dilute aqueous solution prior to permeation with a more concentrated solution, and non-prehydrated GCLs. Tests with DW (plotted at an ionic strength = 1 mM), exhibit low *k* (i.e., $k < 2\text{-}3 \times 10^{-11}$ m/s). However, at low σ', GCL *k* generally increases with increasing ionic strength by up to five orders of magnitude relative to tests with DW. A broad scatter is evident for a given concentration due to both the specific permeant solution chemistry (discussed subsequently), and the specific characteristics of the bentonite and GCL (granule size, fraction of montmorillonite in the bentonite, size of needle-punching fibers). Increased σ' generally results in a lower *k* for a given ionic strength solution. Thus, the hydraulic performance of a GCL is fundamentally linked to both the concentration of the permeant solution, and the stress conditions. The data scatter supports the need for application specific *k* testing with representative permeant liquids and stress conditions.

Data meeting the termination criteria listed for Figure 3 for tests at low σ' are shown separated by permeant composition in Figure 4. Permeant liquids are separated into DW, solutions containing only monovalent cations (e.g., a solution containing potassium chloride, KCl dissolved in DW), solutions containing only divalent cations (e.g., a solution containing calcium chloride, $CaCl_2$, dissolved in DW), solutions containing only trivalent cations (e.g., a solution containing aluminum chloride, $AlCl_3$, dissolved in DW), solutions containing simple mixtures of salts (e.g., a solution containing a blend of KCl and $CaCl_2$ dissolved in deionized water), solutions containing synthetic leachates prepared to mimic a real leachate chemistry (e.g., synthetic municipal solid waste leachate containing numerous cations and anions dissolved in DW), and real leachates (leachates collected from the field).

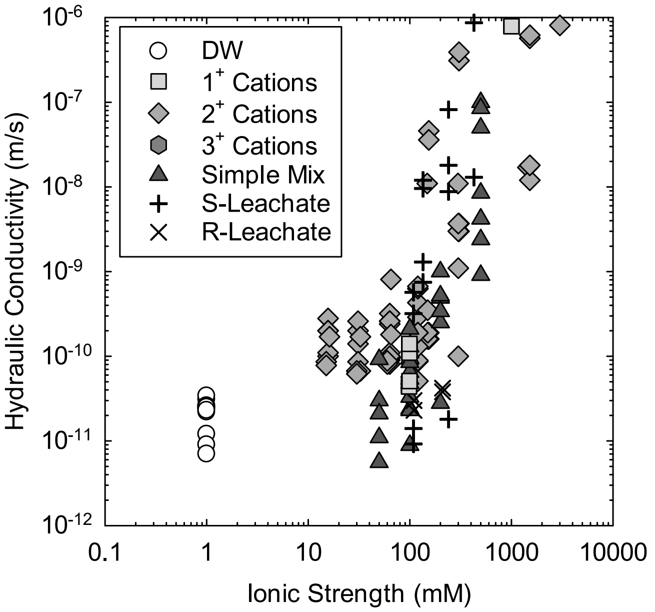

Figure 4 Hydraulic conductivity under low effective stress (16-24 kPa) as a function of the ionic strength of the permeant solution for GCLs permeated with deionized water (DW), monovalent cations only (1^+ Cations), divalent cations only (2^+ Cations), trivalent cations only (3^+ Cations), simple salt solutions containing only monovalent and divalent cations (Simple Mix), synthetic leachate (S-Leachate), and real leachate (R-Leachate). Data from Jo et al. (2004), Kolstad et al. (2004), Jo et al. (2005), Lee and Shackelford (2005a, 2005b), Lee et al. (2005), Benson et al. (2014), Bradshaw and Benson (2014), Bradshaw et al. (2016). Tests with deionized water are plotted at an ionic strength = 1 mM.

For a given solution ionic strength, the divalent-only solutions exhibit a relatively higher *k* than the monovalent-only solutions. This effect is discussed in detail by Kolstad et al. (2004), and quantified in terms of the ratio of monovalent-to-divalent cations (RMD). Permeation of GCLs with salt solutions containing simple mixtures also yields a lower *k* than permeation with a solution containing divalent-only cations due to the higher RMD (higher relative proportion of monovalent cations) in these solutions. Data for tests on synthetic and real leachates exhibit multiple orders-of-magnitude variation in *k* for a given ionic strength due to the variability in real leachate chemistries, and the specific GCL tested. All else being equal, a GCL will perform better containing an aqueous solution with a higher preponderance of monovalent cations than a solution that contains primarily divalent cations. Ongoing research at Colorado State University is aimed at understanding the performance thresholds of GCLs with real leachates from energy and mining wastes.

3.2 Swell Index

Swelling of the bentonite component of GCLs is used as an indicator parameter of both the potential for hydraulic incompatibility (i.e., potential for high *k* with a specific permeant solution) and as an indicator of bentonite quality (i.e. is the bentonite sufficiently high-swelling Na-bentonite for use in a GCL). Swell index tests are performed in accordance with ASTM D5890, and consist of adding two grams of finely ground bentonite into a 100-mL graduate cylinder in a sufficiently slow manner so to allow the bentonite to fully slack, hydrate, and freely swell. The settled volume of swollen bentonite then is recorded as mL of swell per two grams of dry bentonite.

The swell index of bentonite from GCLs in a variety of hydration solutions is shown in Figure 5. Hydrating solutions are separated into the categories used in Figure 4.

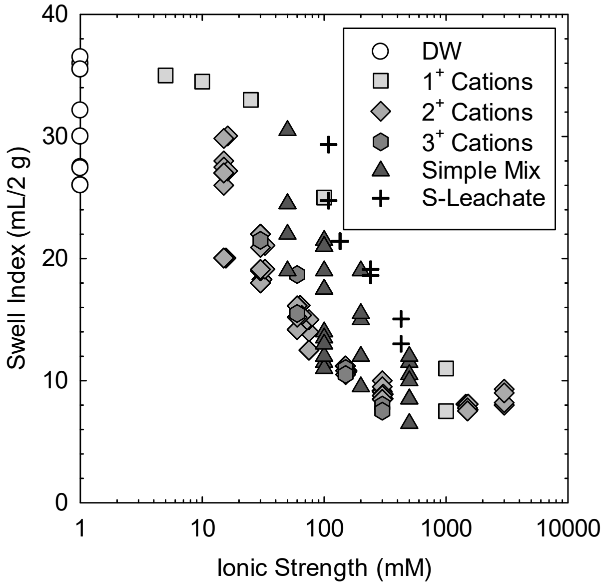

Figure 5 Swell index as a function of the ionic strength of the hydrating solution for GCLs permeated with deionized water (DW), monovalent cations only (1^+ Cations), divalent cations only (2^+ Cations), trivalent cations only (3^+ Cations), simple salt solutions containing only monovalent and divalent cations (Simple Mix), synthetic leachate (S-Leachate), and real leachate (R-Leachate). Data from Jo et al. (2001), Jo et al. (2004), Kolstad et al. (2004), Jo et al. (2005), Lee and Shackelford (2005a, 2005b), Lee et al. (2005), Benson et al. (2014), Bradshaw and Benson (2014), Bradshaw et al. (2016). Tests with DW are plotted at an ionic strength = 1 mM.

A minimum swell index of 24 mL/2 g in DW is a standard specification for the bentonite component of GCLs (e.g., refer to GRI-GCL3; GRI 2016). Bentonite from GCLs (Figure 5) exceed the minimum swell index threshold of 24 mL/2 g with DW, and in dilute hydrating solutions. However, as the ionic strength of the hydrating solution increases, swell index decreases (Figure 5). At high ionic strengths (> 100 mM) bentonite exhibits a swell index less than 10 mL/2 g, which is in the range typical for calcium bentonite (Ca-bentonite).

Similar to data for *k* (Figure 4), swell index is relatively higher for a given ionic strength with monovalent-only hydrating solution, relatively lower for a divalent- or trivalent-only hydrating solution, and intermediate for hydrating solutions that are simple salt mixtures. Data shown in Figure 5 for synthetic leachates are primarily monovalent (refer to Benson et al. 2014), and mimic the results of tests with monovalent-only solutions.

The relationship between *k* and swell index is shown in Figure 6 for tests conducted with the same solution; hydrating and permeant solutions are separated into the categories used in Figure 4. Swell index tests are used as an indicator for the *k* of a GCL (at low σ') when conducted with the same solution. For example, a swell index greater than 14 mL/2 g generally correlates to high *k* (> 10^{-10} m/s), and a swell index less than 20 mL/2 g generally correlates to low *k* (< 2-3 × 10^{-11} m/s). However, for a given swell index, *k* may vary up to four orders of magnitude. Thus, swell index is a useful indicator for GCL *k*, but does not replace *k* tests conducted to hydraulic and chemical equilibrium.

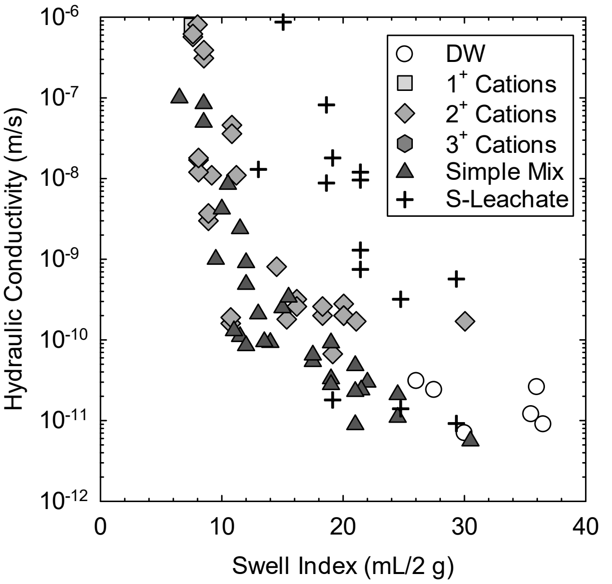

Figure 6 Hydraulic conductivity under low effective stress (16-24 kPa) as a function of swell index in the same solution for GCLs permeated with deionized water (DW), monovalent cations only (1^+ Cations), divalent cations only (2^+ Cations), trivalent cations only (3^+ Cations), simple salt solutions containing only monovalent and divalent cations (Simple Mix), synthetic leachate (S-Leachate), and real leachate (R-Leachate). Data from Jo et al. (2004), Kolstad et al. (2004), Jo et al. (2005), Lee and Shackelford (2005a, 2005b), Lee et al. (2005), Benson et al. (2014), Bradshaw and Benson (2014), Bradshaw et al. (2016).

3.3 Enhanced Bentonites

Recognition of the sensitivity of GCLs to adverse interactions in environmental containment systems has spurred the development of bentonites amended for enhanced performance in hydraulic barrier applications (Onikata and Kondo 1996, Flynn et al. 1998, Lin et al. 2000, Onikata et al. 1999, Trauger and Darlington 2000, Katsumi et al. 2001, Schroeder et al. 2001, Ashmawy et al. 2002, Kolstad et al. 2004, Katsumi et al. 2008, Di Emidio 2010, Di Emidio et al. 2010, Mazzieri et al. 2010, Di Emidio et al. 2011, Mazzieri and Pasqualin 2011, Liu et al. 2012, Scalia et al. 2014, 2018). Enhanced bentonites are engineered to minimize transport processes by maintaining low *k*, membrane behavior, and sealing ability in solutions that are typically incompatible with unamended Na-bentonite, such as high ionic strength and multivalent-cation laden solutions (the incompatibility of GCLs containing unamended Na-bentonite in these solutions is illustrated in Figure 4). Bentonite amendments include: addition of 15-45% propylene carbonate to form multi-swellable bentonite, MSB (Onikata and Kondo 1996, Onikata et al. 1999, Lin et al. 2000, Katsumi et al. 2008), addition of 2-16% Na-carboxymethylcellulose (Na-CMC) to form HYPER-clay, HC (Di Emidio et al. 2010, 2011); prehydrated to a water content of ~43% using a dilute aqueous solution containing Na-CMC and methanol followed by subsequent densification by calendaring to for a dense-prehydrated GCLs, DPH-GCLs (Flynn et al. 1998, Kolstad et al. 2004, Mazzieri et al. 2010, Mazzieri and Pasqualin 2011); in situ polymerization of acrylic acid to form polyacrylate to form a bentonite-polyacrylate composite, BPC (Scalia et al. 2014, Benson et al. 2014); and multiple manufactured products with proprietary additives generally termed contaminant resistant clays, CRCs (Ashmawy et al. 2002).

The *k* of enhanced bentonites as a function of ionic strength is compared to GCLs containing unamended Na-bentonite in Figure 7. At high ionic strengths (> 200 mM), relatively low *k* for a given ionic strength is exhibited by MSB-GCLs, DPH-GCLs, and BPC-GCLs. Data in Figure 7 illustrates that MSB-GCLs are less sensitive to higher ionic strength solutions (200 mM < ionic strength < 700 mM) than GCLs containing unamended bentonite, but still exhibit increased *k* at ionic strengths > 700 mM (Lin et al. 2000, Katsumi et al. 2008).

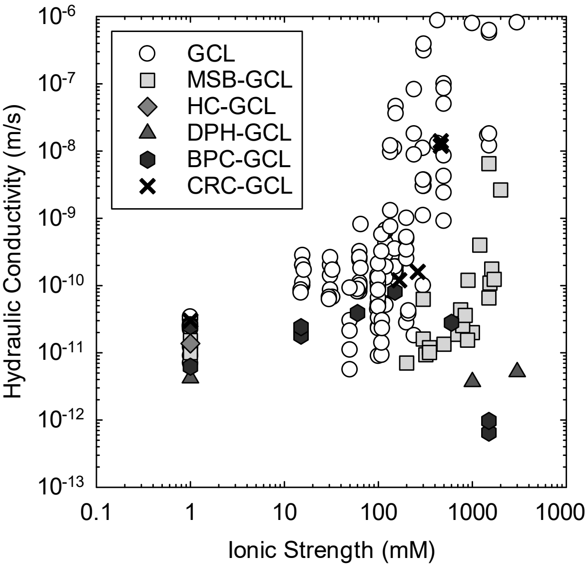

Figure 7 Hydraulic conductivity as a function of the ionic strength of the permeant solution for GCLs (data from Jo et al. 2004, Kolstad et al. 2004, Jo et al. 2005, Lee and Shackelford 2005a, 2005b, Lee et al. 2005, Benson et al. 2014, Bradshaw and Benson 2014, Bradshaw et al. 2016) and GCLs containing multi-swellable bentonite (MSB; data from Lin et al. 2000, Katsumi et al. 2008), HYPER-clay (HC; data from Di Emidio et al. 2011), dense-prehydrated bentonite (DPH; data from Kolstad et al. 2004, Mazzieri et al. 2010, Mazzieri and Pasqualin 2011), bentonite-polyacrylate composite (BPC; data from Scalia et al. 2014), and contaminant resistant clay (CRC; data from Ashmawy et al. 2002). Tests with deionized water are plotted at an ionic strength = 1 mM.

Both DPH-GCLs, and CRC-GCLs exhibit lower *k* when permeated with high ionic strength solutions (> 700 mM) than when permeated with DW (plotted at ionic strength = 1 mM). These data illustrate the potential functionality of GCLs containing enhanced bentonites for containment of high ionic strength solutions. However, as illustrated by data presented in Figure 7 for CRC-GCLs (containing proprietary additives), not all amended bentonites exhibit enhanced performance; CRC-GCLs shown in Figure 7 exhibit behavior typical of GCLs containing unamended bentonite.

The relationship between swell index and the ionic strength of the hydrating solution is shown in Figure 8 and is compared to bentonite from GCLs containing unamended bentonite. Both material from BPC-GCLs and HC-GCLs exhibit greater swelling in DW, and low ionic strength hydrating solutions, than unamended bentonite from a GCL. Materials from MSB-GCLs also exhibit enhanced swelling in mid-range ionic strength solutions (20 mM < ionic strength < 700 mM); however, these data are only for tests conducted with homoionic monovalent (viz. NaCl) hydrating solutions. All materials exhibit similar decreases in swell with increased ionic strength hydrating solutions (Figure 8), such that all materials exhibit swell indices like Ca-bentonite when hydrated in solutions with ionic strength > 700 mM.

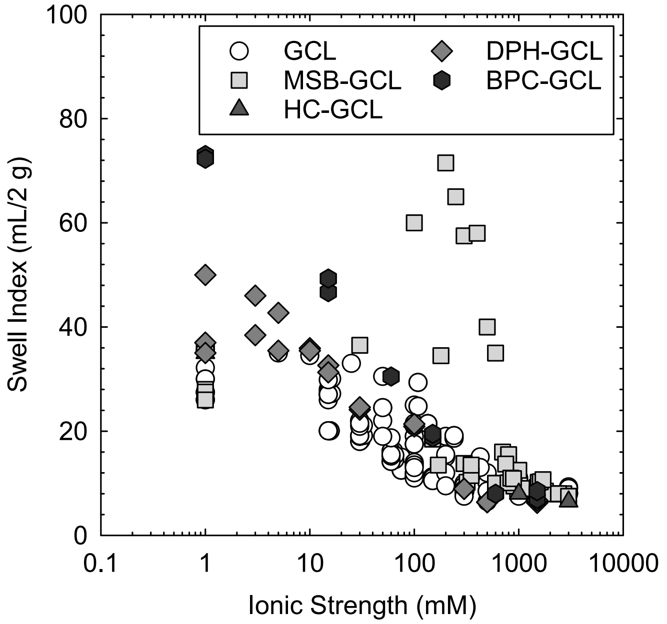

Figure 8 Swell index as a function of the ionic strength of the hydrating solution for GCLs (data from Jo et al. 2004, Kolstad et al. 2004, Jo et al. 2005, Lee and Shackelford 2005a, 2005b, Lee et al. 2005, Benson et al. 2014, Bradshaw and Benson 2014, Bradshaw et al. 2016) and GCLs containing multi-swellable bentonite (MSB; data from Lin et al. 2000, Katsumi et al. 2008), HYPER-clay (HC; data from Di Emidio et al. 2011), dense-prehydrated bentonite (DPH; data from Kolstad et al. 2004, Mazzieri et al. 2010, Mazzieri and Pasqualin 2011), bentonite-polyacrylate composite (BPC; data from Scalia et al. 2014), and contaminant resistant clay (CRC; data from Ashmawy et al. 2002). Tests with deionized water are at an ionic strength = 1 mM.

The *k* of enhanced bentonites is shown against swell index in the same solution in Figure 9, and data for GCLs containing un-amended Na-bentonite are include for comparison. As discussed for Figure 6, GCLs show a correlation between *k* and swell index, whereby low swell index (< 20 mL/2 g) correlates to high *k*. Conversely, DPH-GCLs, and BPC-GCLs exhibit a disconnect between *k* and swell index. These data illustrate that swell index is not an effective indicator for the *k* of DPH-GCLs or BPC-GCLs to chemical solutions, i.e., solutions with the potential to yield high *k* and reduced swell index (Scalia et al. 2014). Ongoing research at Colorado State University is aimed at understanding the disconnect of *k* and swelling in enhanced bentonites.

4. SEMIPERMEABLE MEMBRANE BEHAVIOR

4.1 Significance in GCLs

The potential significance of membrane behavior in GCLs is illustrated by the results in Figure 10, where ω is shown for GCL specimens as a function of the salt (KCl) concentration of the source solution circulated across the top boundary of the specimen, C_{ot} (see Figure 2), for specimens of a GCL at different void ratios, *e*, as reported by Malusis and Shackelford (2002a) and Meier et al. (2014). Note that all the results shown in Figure 10 were based on circulating DW across the bottom of the specimen such that C_{ob} = 0 (see Figure 2).

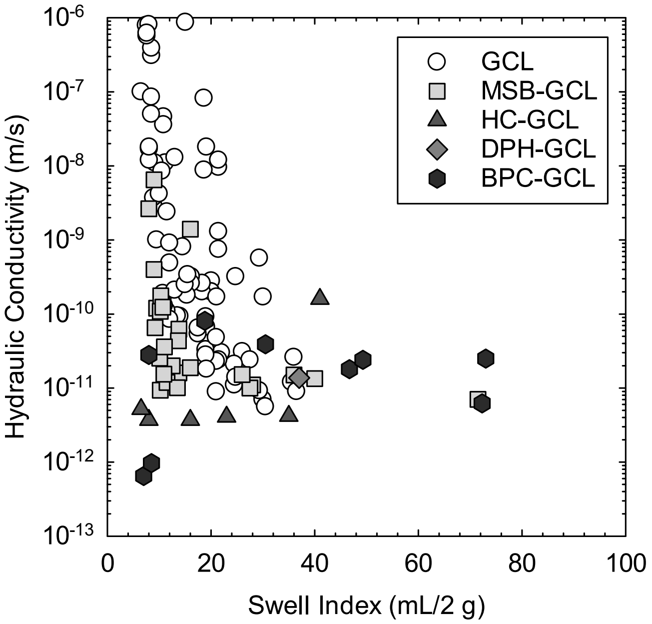

Figure 9 Hydraulic conductivity as a function of swell index in the same solution for GCLs (data from Jo et al. 2004, Kolstad et al. 2004, Jo et al. 2005, Lee and Shackelford 2005a, 2005b, Lee et al. 2005, Benson et al. 2014, Bradshaw and Benson 2014, Bradshaw et al. 2016) and GCLs containing multi-swellable bentonite (MSB; data from Lin et al. 2000, Katsumi et al. 2008), HYPER-clay (HC; data from Di Emidio et al. 2011), dense-prehydrated bentonite (DPH; data from Kolstad et al. 2004, Mazzieri et al. 2010, Mazzieri and Pasqualin 2011), bentonite-polyacrylate composite (BPC; data from Scalia et al. 2014), and contaminant resistant clay (CRC; data from Ashmawy et al. 2002).

For the data in Figure 10 from Malusis and Shackelford (2002a), ω decreased from a high value of 0.68 (68 %) for the lowest C_{ot} of 3.9 mM KCl and the lowest *e* of 2.85 to a low value of 0.07 (7 %) for the highest C_{ot} of 47 mM KCl and the highest *e* of 3.76. Thus, substantial membrane behavior was observed for the GCL specimen exposed to a simple salt solution at relatively high void ratios, although the membrane efficiency decreased with increasing source salt concentration (C_{ot}) and increasing *e*. Since none of the GCL specimens was a perfect membrane, some of the pores within the bentonite of the GCL were accessible to the invading Cl^- and K^+, such that the increase C_{ot} resulted in an increase in pore-water concentrations of the salt ions leading to greater compression of the DDLs associated with individual bentonite particles, larger pore openings, and lesser solute restriction. Similarly, higher *e* correlated with larger and less restrictive pores and, therefore, lower ω. Finally, although the salt concentrations were relatively dilute (3.9 to 47 mM), such dilute concentrations can still be greater than regulatory compliance concentrations, such as the maximum contaminant levels (MCLs), by as much as several orders of magnitude depending on chemical species (Malusis et al. 2003). Thus, membrane behavior can still be relevant for many practical applications involving the use of GCLs as chemical containment barriers.

The trends in ω versus C_{ot} shown in Figure 10 based on the data from Malusis and Shackelford (2002a) tend to be semi-logarithmic linear over the narrow range of KCl concentrations evaluated (i.e., 3.9 to 47 mM). However, the results from Meier et al. (2014) shown in

Figure 10 illustrate that the semi-logarithmic trend becomes nonlinear at higher concentrations, which also has been illustrated elsewhere for bentonites (Kemper and Rollins 1966, Kemper and Quirk 1972) and a compacted sand-bentonite barrier (Meier and Shackelford 2017). For example, for the GCL evaluated by Meier et al. (2014), ω decreased from 0.096 (9.6 %) at 20 mM KCl to 0.000087 (0.00087 %) at 400 mM KCl. Thus, these results indicate that the membrane behavior may persist at concentrations that would be far in excess of those based on a linear extrapolation of the semi-logarithmic trends in ω versus C_{ot} illustrated by Malusis and Shackelford (2002a) and others. This persistent may have important ramifications for the existence of membrane behavior in GCLs used for chemical containment barriers. However, more data are needed for lower *e* and other types of salts (e.g., $CaCl_2$) and chemical solutions.

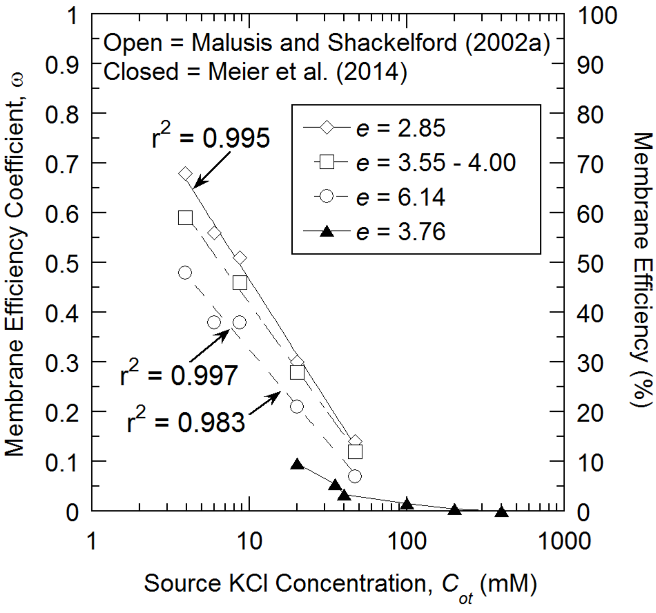

Figure 10 Membrane efficiency of geosynthetic clay liner (GCL) specimens at different void ratios (*e*) as a function of the source potassium chloride concentration (KCl) circulated across the top of the specimen (data from Malusis and Shackelford 2002a and Meier et al. 2014)

For example, Shackelford and Lee (2003) showed that a GCL specimen initially exhibited a membrane efficiency of 52 % (ω = 0.52) when exposed to a concentration difference of 5 mM $CaCl_2$ solution, but that the membrane efficiency degraded over time and eventually became virtually nil (i.e., ω = 0.016) after 35 d, which corresponded exactly with the time required to reach steady-state diffusion of Ca^{2+} through the GCL. They attributed the degradation of membrane behavior to exposure of the bentonite to Ca^{2+}, which compressed the DDLs and expanded the pore space available for solute migration. However, the *e* of the specimen was relatively high (2.46) such that greater resistance to membrane degradation may have occurred with a more compressed specimen.

4.2 Effect of Effective Stress

As previously noted, ω tends to increase with a decrease in *e*. Since a decrease in *e* is known to correlate with an increase in σ', then the expectation is that ω also should increase with increase in σ'.

For example, consider the results shown in Figure 11 from Kang and Shackelford (2010a) and Kang and Shackelford (2011).

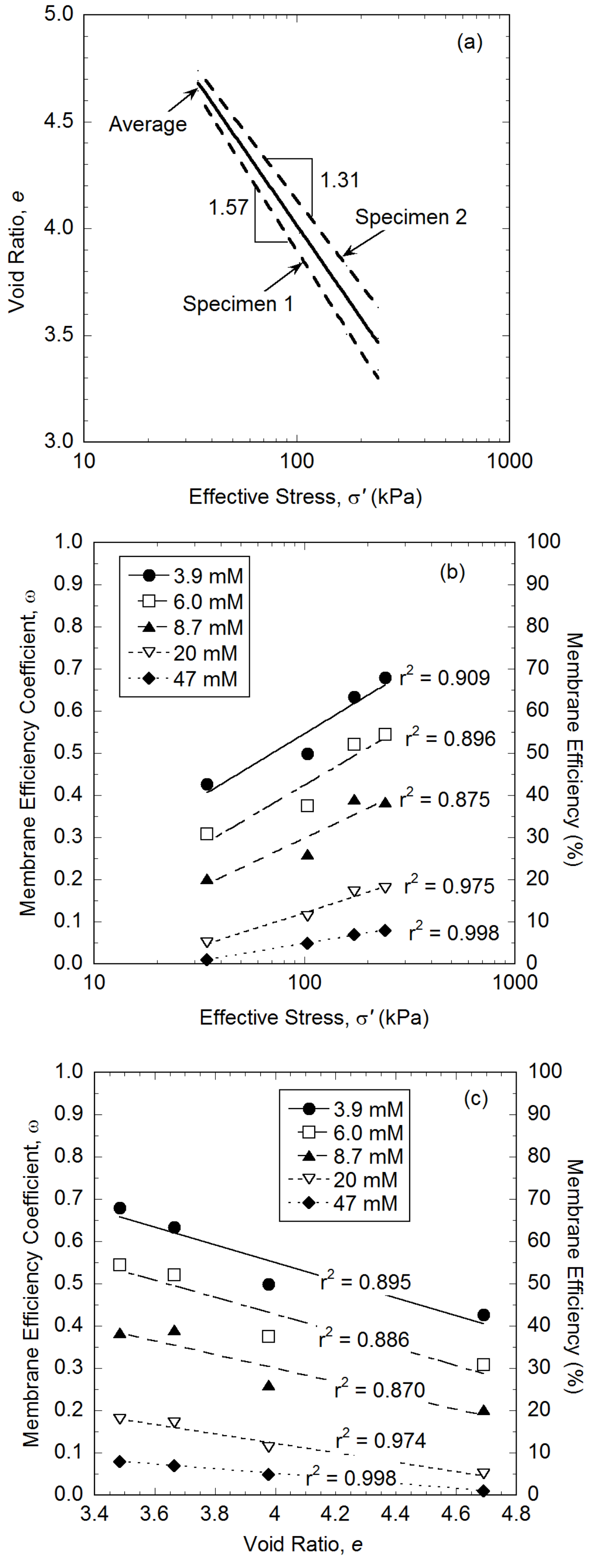

Figure 11 Effect of void ratio and effective stress on the membrane efficiency of a geosynthetic clay liner (GCL): (a) void ratio versus effective stress (data from Kang and Shackelford 2010a); (b) membrane efficiency versus effective stress as a function of potassium chloride (KCl) concentration (data from Kang and Shackelford 2011); (c) membrane efficiency versus void ratio stress as a function of KCl concentration.

In Figure 11a, the consolidation behavior for two specimens of the same GCL based on the results of tests conducted in a triaxial cell under isotropic states of stress are shown. As noted by Kang and Shackelford (2010a), neither GCL specimen exhibited stress history, such that the consolidation behavior of the GCL was analogous to that of normally consolidated clay.

In Figure 11b, the effect of σ' on the measured ω of the same GCL based on membrane tests conducted using a flexible-wall cell and subjected to different source concentrations of KCl (C_{ot}) as reported by Kang and Shackelford (2011) is illustrated. At least three observations are readily apparent from the results shown in Figure 11b. First, for a given C_{ot} of KCl, ω increased with increasing σ', as expected. Second, the increase in ω with increasing σ' was more pronounced with decreasing C_{ot} of KCl, because a decrease in C_{ot} results in an increase in ω (Figure 10). Third, the trends in ω versus the logarithm of σ' (ω – log σ') were approximately linear, with the linearity increasing with increasing C_{ot} of KCl, because an increase in C_{ot} tends to suppress membrane behavior, such that the range in ω with increasing C_{ot} was reduced resulting in less scatter in the data and higher coefficients of determination (r^2).

Finally, the correlation between ω and *e* based on the average of the results shown in Figure 11a and the results shown in Figure 11b is shown in Figure 11c. As expected, ω tends to decrease with increase in *e*, with the decrease in ω being more pronounced with decreasing source concentration (C_{ot}) of KCl.

Although the results shown in Figure 11 are limited in several ways (range of *e*, type and concentrations of salt, quality of bentonite comprising the GCL, etc.), the results suggest that the membrane behavior of GCLs under higher stresses (lower *e*) may be even more significant than that shown in Figure 10. In addition, since an increase in σ' also is known to increase the resistance of GCLs to chemical attack (e.g., Shackelford et al. 2000), the adverse effect of higher salt concentrations on ω also may be minimized or prevented in applications involving the use of GCLs under high σ'.

4.3 Effect of Solute Diffusion

The effect of membrane behavior of a GCL on the steady-state diffusion of KCl through a GCL based on the results of Malusis et al. (2015) is illustrated in Figure 12. The results in Figure 12 pertain to the effective diffusion coefficient, D^*, of KCl as a function of ω for specimens of a GCL at different σ'. For a given σ', D^* tended towards zero as ω approached unity (i.e., $D^* \to 0$ as $\omega \to 1$) as required on the basis that solutes cannot pass through a perfect membrane (see Table 1). Since solute mass flux via diffusion is a function of D^*, a decrease in D^* correlates with a decrease in the steady-state solute mass flux, all other factors being equal (e.g., Shackelford and Daniel 1991; Malusis et al. 2013, Shackelford and Moore 2013; Shackelford 2014). In addition, an increase in σ′ also reduces D^*. Thus, membrane behavior not only restricts solutes from migrating through GCLs, but also reduces the steady-state diffusive mass flux of solutes (e.g., contaminants) through the GCL, and the reduction in steady-state diffusive solute mass flux increases with increasing load (applied stress) on the GCL.

Finally, in open systems such as typically encountered in chemical containment applications, chemico-osmotic counter flow of liquid will occur from a zone of lower solute concentration to a zone of higher solute concentration, or in the direction opposite to that of diffusion, which also can enhance containment of chemicals (Malusis et al. 2003, Whitworth and Ghazifard 2009, Malusis et al. 2017). However, the effect of chemico-osmotic counter flow can vary widely depending on the relative roles of diffusive transport to advective transport and chemico-osmosis to diffusion (Malusis et al. 2017).

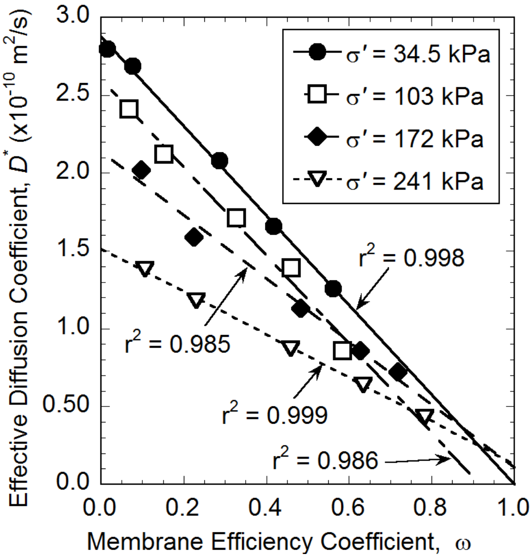

Figure 12 Correlation of effective salt diffusion coefficient form potassium chloride (KCl) with the membrane efficiency of a geosynthetic clay liner as a function of effective stress, σ′ (replotted after Malusis et al. 2015)

Table 1 Limiting values of membrane efficiency coefficient, ω, corresponding to an effective diffusion coefficient, D^*, of zero for chloride diffusion through a GCL as a function of the effective stress based on linear regressions shown in Figure 12

Effective Stress, σ′ (kPa)	ω @ D^* = 0
34.5	1.00
103	0.92
172	1.05
241	1.09

4.4 Polymerized Bentonites

Within the past several years, consideration of the use of chemically modified bentonites as substitutes for traditional Na-bentonite has gained momentum due to the potential for improved chemical resistance (compatibility) and, therefore, improved containment performance (e.g., Bohnhoff et al. 2013, Bohnhoff and Shackelford 2014, Shackelford and Scalia 2016). In particular, a variety of polymerized bentonites has been evaluated for improved containment performance (Di Emidio 2010, Bohnhoff 2012, Scalia 2012). For example, Bohnhoff (2012) and Scalia (2012) evaluated the use of a polymer treated bentonite referred to as a bentonite-polymer composite, BPC (Scalia et al. 2011, 2014), or a bentonite-polymer nanocomposite, BPN (Bohnhoff and Shackelford 2013), for use in GCLs in terms of hydraulic conductivity, diffusion and membrane behavior. The polymerized bentonite exhibited improved hydraulic resistance (Scalia et al. 2014), improved membrane behavior (Bohnhoff et al. 2014), and improved diffusion behavior (Bohnhoff and Shackelford 2015) relative to that for traditional bentonites, but the improved behaviors varied depending on testing conditions and were not necessarily unlimited. The potential use of chemically modified bentonites, in general, and polymerized bentonites, in particular, as substitutes for traditional bentonites in a variety of bentonite-based containment barriers, including GCLs, remains an active area of research and should be of interest for practical containment applications for the foreseeable future.

5. SHEAR STRENGTH

5.1 Effect of Temperature

Elevated temperatures have been shown to affect the mechanical and chemical properties of polymeric materials (e.g., polypropylene, polyethylene, and polyester) commonly used in GCLs (e.g., Farrag 1998, Karademir and Frost 2014). These studies have documented reduced tensile strength, increased elongation at failure, and increased rate and magnitude of creep deformation, which were linked to changes in physical and chemical properties of the polymeric materials. GCLs may experience reduced shear strength in high temperature environments due to degradation of polymeric fibers, and a stress-controlled direct shear apparatus was developed to evaluate the internal shear behavior of GCLs subjected to elevated temperatures.

Ghazi Zadeh and Bareither (2017) conducted stress-controlled direct shear tests at varying temperature on a needle-punched reinforced GCL. Temporal relationships of horizontal deformation for shear tests conducted at an initial normal stress (σ_{ni}) of 20 and 60 kPa are shown in Figure 13 as a function of temperature. For a certain σ_{ni} (e.g., σ_{ni} = 20 kPa in Figure 13), an increase in temperature yielded more pronounced horizontal deformation under a given applied shear stress. This behavior was attributed to reduced tensile strength of the needle-punched fibers with an increase in temperature. The relationship between the ratio of shear stress to normal stress at failure versus test temperature for the six experiments in Figure 13 is shown in Figure 14. Although the data set is limited and some scatter exists, an overall reduction in internal shear strength was observed with an increase in temperature from 20 °C to 80 °C for stress-controlled direct shear experiments conducted at both σ_{ni} = 20 kPa and 60 kPa.

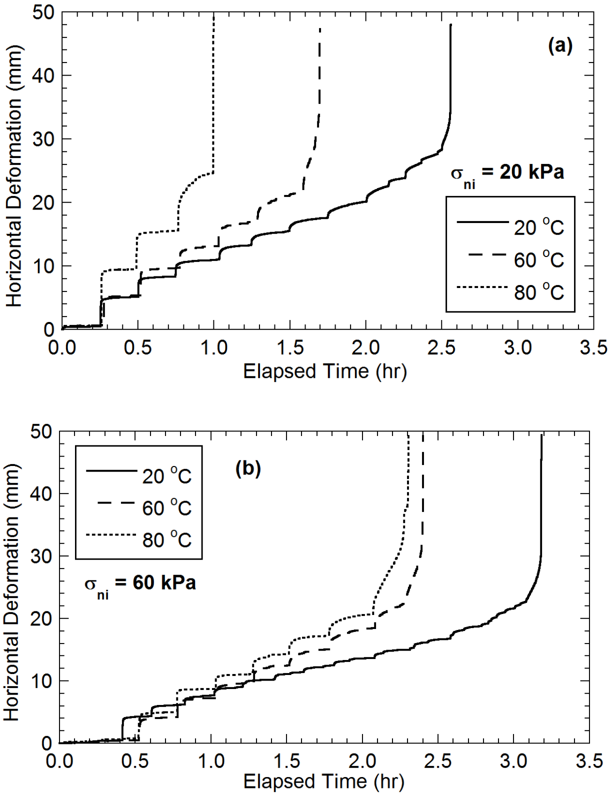

Figure 13 Temporal relationships of horizontal deformation for a non-heat-treated, needle-punched geosynthetic clay liner conducted at (a) initial normal stress (σ_{ni}) = 20 kPa and (b) σ_{ni} = 60 kPa. Experiments were conducted in a stress-controlled direct shear box at temperatures of 20, 60, and 80 °C (Ghazi Zadeh and Bareither 2017).

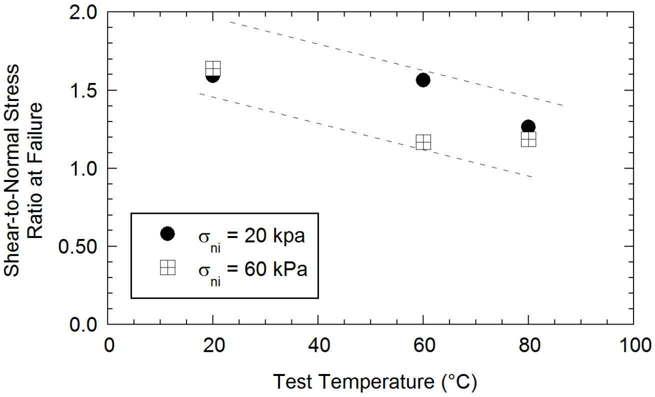

Figure 14 Relationship between the shear-to-normal stress ratio at failure versus test temperature for stress-controlled direct shear experiments conducted at an initial normal stress (σ_{ni}) = 20 kPa and 60 kPa (Ghazi Zadeh and Bareither 2017).

The experiments shown in Figure 13 agree with observations made by Müller et al. (2008) that temperature can reduce the internal shear resistance of internally-reinforced GCLs. Failure was achieved in all experiments conducted by Ghazi Zadeh and Bareither (2017) due to use of DW as the hydration solution and ability to apply high shear stress relative to normal stress to induce failure. However, numerous questions remain pertaining to the mechanisms contributing to the loss of shear resistance, potential for similar strength reduction in other hydration solutions, and assessment of shear behavior as a function of temperature across a broad range of GCLs. Research is ongoing at Colorado State University to address these aforementioned questions.

5.2 Effect of Hydration Solution

Preliminary stress-controlled direct shear tests were conducted to evaluate the effect of hydration solution on internal GCL shear strength. Experiments were conducted following methods outlined in Ghazi Zadeh and Bareither (2017) on a non-heat-treated needle-punched GCL (NHT GCL) and a heat-treated needle-punched GCL (HT GCL) with comparable peel strength. The stress-controlled direct shear experiments described herein were hydrated for 15 d in DW and a synthetic gold mine process solution (Au-PS). The Au-PS was developed to represent an actual mine process solution (Ghazi Zadeh et al. 2017), and had a neutral pH, I = 0.049 M, and RMD = 0.4.

Relationships between the ratio of shear to normal stress (τ/σ_n) and horizontal deformation at the end of each shear load ($\delta_{h\text{-EOL}}$) for the NHT GCL and HT GCL are shown in Figure 15. Shear stress was applied incrementally in a controlled manner and the maximum applied τ was limited to 92.9 kPa for all experiments. The stress-controlled direct shear experiments conducted in DW on both GCLs reached failure at τ = 92.9 kPa. However, the experiments conducted in the Au-PS did not reach failure, but were terminated after reaching τ = 92.9 kPa. The development of internal shear failure in DW and the absence of internal shear failure in a solution that included divalent cations and the potential for cation exchange was also observed by Müller et al. (2008). Thus, increase in the internal shear strength of GCL specimens hydrated with Au-PS was hypothesized to result from cation exchange of divalent cations for monovalent cations in the bentonite.

In general, the shear behaviors measured for specimens hydrated in DW and Au-PS were similar for both GCLs. However, the magnitude of $\delta_{h\text{-EOL}}$ for a given τ increment was greater in the NHT GCL compared to the HT GCL. This difference in $\delta_{h\text{-EOL}}$ was attributed to GCL heat treatment, whereby greater shear deformation developed from a combination of tensile elongation and disentanglement of reinforcement fibers in the NHT GCL compared to tensile elongation of the reinforcement fibers in the heat-treated

GCL. The specimens hydrated in Au-PS yielded the highest τ/σ_n ratios and did not experience internal failure. Although numerous questions remain to be answered regarding the effects of non-standard solution hydration on internal GCL shear strength, the observed influence of Au-PS on internal shear strength indicates the importance of additional research to understand mechanisms contributing to shear behavior of GCLs in non-standard hydration solutions.

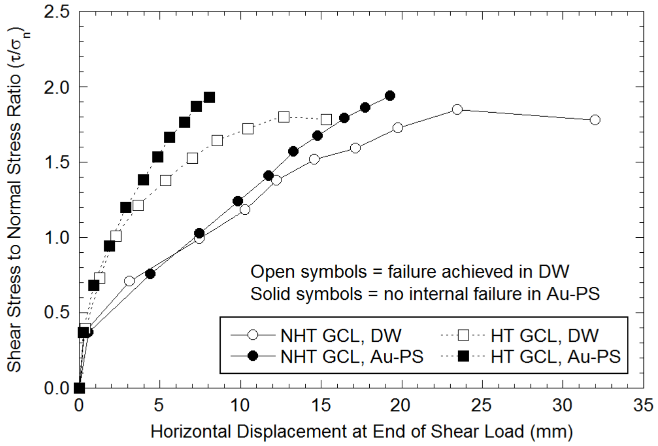

Figure 15 Relationship between the ratio of shear to normal stress (τ/σ_n) and horizontal deformation at the end of shear loading ($\delta_{h\text{-EOL}}$) for a non-heat-treated needle-punched GCL (NHT GCL) and heat-treated needle-punched GCL (HT GCL) hydrated for 15 d in de-ionized water (DW) and a synthetic gold solution (Au-PS). Experiments were performed with an initial normal stress (σ_{ni}) = 20 kPa at a temperature (T) of 20 °C.

6. SUMMARY AND CONCLUSIONS

Geosynthetic clay liners (GCLs) exhibit low hydraulic conductivity, k ($2\text{-}3\times10^{-11}$ m/s), to dilute aqueous solutions. However, interactions with chemical solutions may yield significantly higher k, particularly under low effective stress conditions (16-24 kPa), due to reductions in the swelling of the bentonite component. The swell index test provides a useful indicator for GCL k, but does not replace the need for site-specific k tests to chemical equilibrium to verify GCL k. Enhanced bentonites, i.e., bentonites amended to maintain low k to aqueous chemical solutions that yield high k ($>> 2\text{-}3 \times10^{-11}$ m/s) to unamended bentonites, are shown to exhibit improved k relative to unamended bentonites (although not all enhanced bentonites show improved k). However, while some enhanced bentonites rely on enhanced swelling for improved hydraulic performance, other enhanced bentonites exhibit a disconnect between low k and swelling, such that the swell index test does not appear to be a valid indicator of enhanced bentonite k.

The bentonite component of GCLs has been shown to exhibit significant semipermeable membrane behavior when exposed to dilute concentrations of simple salt solutions (e.g., KCl). Such membrane behavior results from restriction of solute migration due to interaction of the electric fields associated with adjacent, negatively charged bentonite particles, which in turn leads to reduced diffusive solute mass flux and the coupled phenomenon of chemico-osmosis in open systems such as those typically encountered in chemical containment applications. Since all three of these mechanisms (i.e., solute restriction, reduced diffusive mass flux, chemico-osmosis) work in favor of enhancing chemical containment, membrane behavior of GCLs is beneficial to the containment function of GCLs.

The magnitude of membrane behavior observed for GCLs has been shown to increase with decreasing concentration of inorganic chemicals and decreasing e or increasing σ', and has been shown to persist at simplified salt concentrations as high as 400 mM KCl. Also, the substitution of chemically modified bentonites such as polymerized bentonites for traditional Na-bentonites used in GCLs has been shown to improve the membrane, diffusive, and hydraulic performance of the GCLs. However, because of the wide variety of possible chemically modified bentonites and testing conditions, additional research pertaining to the use of chemically modified bentonites in GCLs used for containment applications is needed before widespread commercial use of these materials can occur.

Geosynthetic clay liners used in waste containment applications can be expected to experience variation in temperature and hydration solution relative to conditions typically imposed in laboratory experiments. An increase in test temperature has been shown to reduce the internal shear strength of needle-punched GCLs. This strength reduction is attributed to a decrease in tensile strength of the needle-punched fibers with an increase in temperature, and on-going research is focused on understanding the mechanisms of this observed strength reduction. Hydration of GCLs in non-standard chemical solutions also has been shown to influence the internal shear strength of needle-punched GCLs. An increase in internal strength was observed for GCL specimens hydrated in a synthetic gold mine process solution, which was attributed to cation exchange of divalent for monovalent cations in the bentonite that increased shear strength of the bentonite. Additional research is on-going to understand mechanisms contributing to changes in the internal shear strength of GCLs hydrated in non-standard chemical solutions.

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8. REFERENCES

Ashmawy, A., Darwish, E., Sotelo, N., and Muhammad, N. (2002) "Hydraulic performance of untreated and polymer-treated bentonite in inorganic landfill leachates." Clays and Clay Minerals, 50, Issue 5, pp 546-552.

Benson, C., Chen, J., and Edil, T. (2014) "Engineering properties of geosynthetic clay liners permeated with coal combustion product leachates." Report No. 3002003770, Electric Power Research Institute (EPRI), Palo Alto, CA.

Benson, C., and Meer, S. (2009) "Relative abundance of monovalent and divalent cations and the impact of desiccation on geosynthetic clay liners." Journal of Geotechnical and Geonvironmental Engineering, 133, Issue 5, pp 814-827.

Bradshaw, S., and Benson, C. (2014) "Effect of municipal solid waste leachate on hydraulic conductivity and exchange complex of geosynthetic clay liners." Journal of Geotechnical and Geonvironmental Engineering, 140, Issue 4, 04013038.

Bradshaw, S., Benson, C., and Rauen, T. (2016) "Hydraulic conductivity of geosynthetic clay liners to recirculated municipal solid waste leachates." Journal of Geotechnical and Geoenvironmental Engineering, 142, Issue 2, 04015074.

Bohnhoff, G.L. (2012) Membrane Behavior, Diffusion, and Compatibility of a Polymerized Bentonite for Containment Barrier Applications. Ph.D. Dissertation, Colorado State University, Fort Collins, Colorado, USA.

Bohnhoff, G.L., Sample-Lord, K.M., and Shackelford, C.D. (2016) "Advances in membrane behavior of bentonite-based barriers." Geo-Chicago 2016: Sustainable Geoenvironmental Systems, A. De, K.R. Reddy, N. Yesiller, D. Zekkos, A. Farid, Eds., Geotechnical Special Publication No. 271, ASCE, Reston, Virginia, USA, pp 329-338.

Bohnhoff, G.L., and Shackelford, C.D. (2013) "Improving membrane performance via bentonite polymer nanocomposite." Applied Clay Science, 86, pp 83-98.

Bohnhoff, G.L. and Shackelford, C.D. (2014) "Hydraulic conductivity of chemically modified bentonites for containment barriers." Proceedings, 7th International Conference on Environmental Geotechnics, A. Bouazza, S. Yuen, and B. Brown, Eds., Nov. 10-14, 2014, Melbourne, Australia, Engineers Australia, Barton (ISBN 978-1-922107-23-7), pp 440-447.

Bohnhoff, G.L., and Shackelford, C.D. (2015) "Salt diffusion through a bentonite-polymer composite." Clays and Clay Minerals, 63, Issue 3, pp 145-162.

Bohnhoff, G.L., Shackelford, C.D., Malusis, M.A., Scalia, J., Benson, C.H., Edil, T.B., Di Emiddio, G., Katsumi. T., and Mazzieri, F. (2013) "Novel bentonites for containment barrier applications." Proceedings, 18th International Conference on Soil Mechanics and Geotechnical Engineering-Challenges and Innovations in Geotechnics, P. Delage, J. Desrues, R. Frank, A. Puech, F. Schlosser, Eds., Presses des Ponts, Paris, Vol. 4, pp 2997-3000.

Bohnhoff, G.L., Shackelford, C.D., and Sample-Lord, K.M. (2014) "Calcium resistant membrane behavior of a polymerized bentonite." Journal of Geotechnical and Geoenvironmental Engineering, 140, Issue 3, 04013029.

Bouazza, A. (2002) "Geosynthetic clay liners." Geotextiles and Geomembranes, 20, Issue 1, pp 3-17.

Bradshaw, S. L., Benson, C. H., and Scalia, J. (2013). "Hydration and cation exchange during subgrade hydration and effect on hydraulic conductivity of geosynthetic clay liners." Journal of Geotechnical Geoenvironmental Engineering, 139, Issue 4, pp 526-538.

Breitenbach, A.J. and Athanassopoulos, C. (2013) "Improving the stability of high fill load structures built on low strength geosynthetic interfaces." Geosynthetics 2013, pp 762-772.

Brown, L.C. and Shackelford, C.D. (2007) "Hydraulic conductivity of a geosynthetic clay liner to a simulated animal waste solution." Transactions of the American Society of Agricultural and Biological Engineers, 50, Issue 3, pp 831-841.

Chen, Y.M., Lin, W.A., Zhu, B., and Zhan, Z.T. (2011) “Performance-based design of geosynthetic liner systems.” Geotechnical Journal of the South East Asian Geotechnical Society, 42, Issue 1, pp 66-73.

Conzelmann, J., Scalia IV, J., and Shackelford, C.D. (2017) "Effect of backpressure saturation on hydraulic conductivity of GCLs." Geotechnical Frontiers 2017: Waste Containment, Barriers, Remediation, and Sustainable Geoengineering, T.L Brandon and R.J. Valentine, Eds., Geotechnical Special Publication No. 276, ASCE, Reston, Virginia, USA, pp 227-235.

Daniel, D. (1994) "State-of-the-art: laboratory hydraulic conductivity tests for saturated soils." Hydraulic Conductivity and Waste Contaminant Transport in Soil, ASTM STP 1142, D.E. Daniel and S.J. Trautwein, Eds., ASTM International, West Conshohocken, Pennsylvania, USA, pp 30-78.

Daniel, D.E., Bowders, J.J., Jr., and Gilbert, R.B. (1997) "Laboratory hydraulic conductivity testing of GCLs in flexible-wall permeameters." Testing and Acceptance Criteria for Geosynthetic Clay Liners, L.W. Well, Ed., ASTM STP 1308, pp 208-226.

Daniel, D.E., and Gilbert, R.B. (1996) "Practical methods for managing uncertainties for geosynthetic clay liners." Uncertainty in the Geologic Environment: From Theory to Practice, C.D. Shackelford, P.N. Nelson, and M.J.S. Roth, Eds., ASCE, Reston, Virginia, USA, pp 1331-1346.

Di Emidio, G., Van Impe, W., and Mazzieri, F. (2010) “A polymer enhanced clay for impermeable geosynthetic clay liners.” , 6th International Conference on Environmental Geotechnics, International Society for Soil Mechanics and Geotechnical Engineering, New Delhi, India, pp 963-967.

Di Emidio, G., Van Impe, W., and Flores, V. (2011) "Advances in geosynthetic clay liners: polymer enhanced clays." GeoFrontiers 2011. Advances in Geotechnical Engineering, ASCE, Reston, Virginia, USA, pp 1931-1940.

Di Emidio, G. (2010) Hydraulic Conductivity and Chemico-Osmotic Performance of Polymer Treated Clays. Ph.D. Dissertation, University of Ghent, Ghent, Belgium.

Du Preez, L., Beaman, R., and Watkins, I. (2012) “The use of geosynthetics in major metropolitan landfills in Perth, WA – two case studies.” Geotechnical Engineering Journal of the South East Asian Geotechnical Society, 43, Issue 3, pp 68-70.

Farrag, K. (1998) "Development of an accelerated creep testing procedure for geosynthetics, part II: analysis." Geotechnical Testing Journal, 21, Issue 1, pp 38-44.

Ghazi Zadeh, S. and Bareither, C.A. (2017) "Temperature-dependent shear behavior of geosynthetic clay liners." Geotechnical Frontiers 2017, GSP 280, ASCE, Reston, Virginia, USA, pp 288-298.

Ghazi Zadeh, S., Bareither, C.A., Scalia, J., Shackelford, C.D. (2017) Development of synthetic mining solutions for laboratory testing of geosynthetic clay liners.” Journal of Geotechnical and Geoenvironmental Engineering, in review.

Flynn, B., & Carter, G. (1998) Waterproofing material and method of fabrication thereof. US Patent Number: 6,537,676 B1.

Fox, P. J., and Stark, T. D. (2015) "State-of-the-art report: GCL shear strength and its measurement–ten-year update." Geosynthetics International, 22, Issue 1, pp 3-47.

Hornsey, W.P., Scheirs, J., Gates, W.P., and Bouazza, A. (2010) "The impact of mining solutions/liquors on geosynthetics." Geotextiles and Geomembranes, 28, Issue 2, pp 191–198.

Hsuan, Y. G. (2002) "Approach to the study of durability of reinforcement fibers and yarns in geosynthetic clay liners." Geotextiles and Geomembranes, 20, Issue 1, pp 63-76.

Jo, H., Benson, C., and Edil, T. (2004) "Hydraulic conductivity and cation exchange in non-prehydrated and prehydrated bentonite permeated with weak inorganic salt solutions." Clays and Clay Minerals, 52, Issue 6, pp 661-679.

Jo, H., Benson, C., and Edil, T. (2006) "Rate-limited cation exchange in thin bentonitic barrier layers." Canadian Geotechnical Journal, 43, Issue 4, pp 370-391.

Jo, H., Katsumi, T., Benson, C., and Edil, T. (2001) "Hydraulic conductivity and swelling of non-prehydrated GCLs permeated with single species salt solutions." Journal of Geotechnical and Geoenvironmental Engineering, 127, Issue 7, pp 557-567.

Jo, H.-Y., Benson, C.H., Shackelford, C.D., Lee, J.-M. and Edil, T.B. (2005) "Long-term hydraulic conductivity of a geosynthetic clay liner (GCL) permeated with inorganic salt solutions." Journal of Geotechnical and Geoenvironmental Engineering, 131, Issue 4, pp 405-417.

Kang, J.-B. and Shackelford, C.D. (2009) "Clay membrane testing using a flexible-wall cell under closed-system boundary conditions." Applied Clay Science, 44, Issues 1-2, pp 43-58.

Kang, J.-B. and Shackelford, C.D. (2010a) "Consolidation of a geosynthetic clay liner under isotropic states of stress." Journal of Geotechnical and Geoenvironmental Engineering, 136, Issue 1, pp 253-259.

Kang, J.-B. and Shackelford, C.D. (2010b) "Membrane behavior of compacted clay liners." Journal of Geotechnical and Geoenvironmental Engineering, 136, Issue 10, pp 1368-1382.

Kang, J.-B. and Shackelford, C.D. (2011) "Consolidation enhanced membrane behavior of a geosynthetic clay liner." Geotextiles and Geomembranes, 29, Issue 6, pp 544-556.

Karademir, T., and Frost, J. D. (2014) "Micro-scale tensile properties of single geotextile polypropylene filaments at elevated temperatures." Geotextiles and Geomembranes, 42, issue 3, pp

201-213.

Katsumi, T., Ishimori, H., Ogawa, A., Yoshikawa, K., Hanamoto, K., and Fukagawa, R. (2007) "Hydraulic conductivity of nonprehydrated geosynthetic clay liners permeated with inorganic solutions and waste leachates." Soils and Foundations, 47, Issue 1, pp 79-96.

Katsumi, T., Ishimori, H, Onikata, M., and Fukagawa, R. (2008) "Long-term barrier performance of modified bentonite materials against sodium and calcium permeant solutions." Geotextiles and Geomembranes, 26, Issue 1, pp 14-30.

Kemper, W.D. and Quirk, J.P. (1972) "Ion mobilities and electric charge of external clay surfaces inferred from potential differences and osmotic flow." Soil Science Society of America Proc., 36, Issue 3, pp 426-433.

Kemper, W.D. and Rollins, J.B. (1966) "Osmotic efficiency coefficients across compacted clays." Soil Science Society of America Proc., 30, Issue 5, pp 529-534.

Koerner, R.M. (2005) Geosynthetic Clay Liners, Chapter 6: Designing with Geosynthetics, 5th Ed., Pearson Prentice Hall, Upper Saddle River, New Jersey, USA, pp 630-668.

Koerner, R.M. and Daniel, D.E. (1995) "A suggested methodology for assessing the technical equivalency of GCLs to CCLs." Geosynthetic Clay Liners, R. M Koerner, E. Gartung, and H. Zanzinger, Eds., Balkema, Rotterdam, pp 73-98.

Kolstad, D.C. (2000) Compatibility of Geosynthetic Clay Liners (GCLs) with Multi-Species Inorganic Solutions. M.S. Thesis, University of Wisconsin at Madison, Wisconsin, USA.

Kolstad, D.C., Benson, C.H., and Edil, T.B. (2004) "Hydraulic conductivity and swell of nonprehydrated geosynthetic clay liners permeated with multispecies inorganic solutions." Journal of Geotechnical and Geoenvironmental Engineering, 130, Issue 12, pp 1236-1249.

Koerner, R.M., Soong, T.Y., Koerner, G.R., and Gontar, A. (2001) "Creep testing and data extrapolation of reinforced GCLs." Geotextiles and Geomembranes, 19, Issue 7, pp 413-425.

Lee, J.-M. and Shackelford, C.D. (2005) "Impact of bentonite quality on hydraulic conductivity of geosynthetic clay liners." Journal of Geotechnical and Geoenvironmental Engineering, 131, Issue 1, pp 64-77.

Lee, J.-M. and Shackelford, C.D. (2005) "Concentration dependency of the prehydration effect for a geosynthetic clay liner." Soils and Foundations, 45, Issue 4, pp 27-41.

Lee, J.-M., Shackelford, C.D., Benson, C.H., Jo, H.-Y., and Edil, T.B. (2005) "Correlating index properties and hydraulic conductivity of geosynthetic clay liners." Journal of Geotechnical and Geoenvironmental Engineering, 131, Issue 11, pp 1319-1329.

Lin, L.-C. and Benson, C.H. (2000) "Effect of wet-dry cycling of swelling and hydraulic conductivity of GCLs." Journal of Geotechnical and Geoenvironmental Engineering, 126, Issue 1, pp 40-49.

Liu, Y., Gates, W.P., and Bouazza, A. (2012) “Improvement on the performance of geosynthetic clay liners using polymer modified bentonite.” Geotechnical Journal of the South East Asian Geotechnical Society, 43, Issue 3, pp 43-45.

Malusis, M.A., Kang, J.-B., and Shackelford, C.D. (2013) "Influence of membrane behavior on solute diffusion through GCLs." Coupled Phenomena in Environmental Geotechnics, M. Manassero, A. Dominijanni, S. Foti, and G. Musso, Eds., July 1-3, 2013, Torino, Italy, CRC Press/Balkema, Taylor & Francis Group, London, pp 267-274.

Malusis, M.A., Kang, J.-B., and Shackelford, C.D. (2015) "Restricted salt diffusion in a geosynthetic clay liner." Environmental Geotechnics, 2, Issue 2, pp 68-77.

Malusis, M.A., Scalia, J., Norris, A.S., and Shackelford, C.D. (2017) "Quantifying the significance of chemico-osmotic counter-advection on solute transport through semipermeable clay barriers." International Symposium on Coupled Phenomena in Environmental Geotechnics (CPEG2), September 6-7, 2017, Leeds, University of Leeds, UK, paper 51.

Malusis, M.A. and Shackelford, C.D. (2002a) "Chemico-osmotic efficiency of a geosynthetic clay liner." Journal of Geotechnical and Geoenvironmental Engineering, 128, Issue 2, pp 97-106.

Malusis, M.A. and Shackelford, C.D. (2002b) "Coupling effects during steady-state solute diffusion through a semipermeable clay membrane." Environmental Science and Technology, 36, Issue 6, pp 1312-1319.

Malusis, M.A., Shackelford, C.D., and Olsen, H.W. (2001) "A laboratory apparatus to measure chemico-osmotic efficiency coefficients for clay soils." Geotechnical Testing Journal, 24, Issue 3, pp 229-242.

Malusis, M.A., Shackelford, C.D., and Olsen, H.W. (2003) "Flow and transport through clay membrane barriers." Engineering Geology, 70, Issues 2-3, pp 235-248.

Mazzieri, F., Pasqualini, E., and Emidio, G. (2010) "Migration of heavy metals through conventional and factory-prehydrated GCL materials." Proceedings, 6th International Conference on Environmental Geotechnics, International Society for Soil Mechanics and Geotechnical Engineering, New Delhi, India, pp 963-967.

Mazzieri, F., and Pasqualini, E. (2011) "Retention of heavy metals in conventional and factory-prehydrated GCL materials." Geo-Frontiers 2011, ASCE, Reston, Virginia, USA, pp 1941-1950.

McBride M. (1994) Environmental Chemistry of Soils. Oxford University Press, New York.

Meer, S., and Benson, C. (2007) "Hydraulic conductivity of geosynthetic clay liners exhumed from landfill final covers." Journal of Geotechnical and Geoenvironmental Engineering, 133, Issue 5, pp 550-563.

Meier, A.J., Sample-Lord, K.M., Castelbaum, D., Kallase, S.A., Moran, B.P., Ray, T.H., and Shackelford, C.D. (2014) "Persistence of semipermeable membrane behavior for a geosynthetic clay liner." Proceedings, 7th International Conference on Environmental Geotechnics, A. Bouazza, S. Yuen, and B. Brown, Eds., Nov. 10-14, 2014, Melbourne, Australia, 2014 Engineers Australia, Barton (ISBN 978-1-922107-23-7), pp 496-503.

Meier, A.J. and Shackelford, C.D. (2017) "Membrane behavior of compacted sand-bentonite mixture." Canadian Geotechnical Journal, 54, Issue 9. pp 1284-1299.

Mesri, G. and Olson, R. (1970) "Shear strength of montmorillonite." Géotechnique, 20, Issue 3, pp 261-270.

Mitchell, J.K. and Soga, K. (2005) Fundamentals of Soil Behavior, 3rd ed., John Wiley and Sons, Inc., New York

Müller, W.W., Jakob, I., Seeger, S., and Tatzky-Gerth, R., (2008) "Long-term shear strength of geosynthetic clay liners." Geotextiles and Geomembranes, 26, Issue 2, pp 130-144.

Naka, A., Katsumi, T., Flores, G., Inui, T., Ohta, T., Urakoshi, T., and Ishihara, T. (2012) "Evaluation of mineral barriers against acid rock drainage." Geotechnical Journal of the South East Asian Geotechnical Society, 43, Issue 3, pp 35-42.

Ng, H.B., and Ramsey, B. (2012) "Geosynthetic lining systems for modern waste facilities – experiences in developing Asia." Geotechnical Journal of the South East Asian Geotechnical Society, 43, Issue 3, pp 62-67.

Onikata, M., Kondo, M., & Kamon, M. (1996) "Development and characterization of a multiswellable bentonite." Environmental Geotechnics. Taylor and Francis, Rotterdam, pp 587-590.

Onikata, M., Kondo, M., Hayashi, N., & Yamanaka, S. (1999) "Complex formation of cation-exchanged montmorillonites with propylene carbonate: osmotic swelling in aqueous electrolyte solutions." Clays and Clay Minerals, 47, Issue 5, pp 672-677.

Petrov, R., Rowe, K., and Quigley, R. (1997) "Selected factors influencing GCL hydraulic conductivity." Journal of Geotechnical and Geoenvironmental Engineering, 123, Issue 8, pp 683-695.

Rowe, R.K. (1998) "Geosynthetics and the minimization of contaminant migration through barrier systems beneath solid waste." 6th International Conference on Geosynthetics, Industrial Fabrics Association International (IFAI), Roseville, Minnesota, USA, Vol. 1, pp 27-103.

Rowe, R.K. (2005) "Long-term performance of contaminant barrier systems." Géotechnique, 55, Issue 9, pp 631-678.

Rowe, R.K. (2006) "Some factors affecting geosynthetics used for geoenvironmental applications." 5th International Conference on Environmental Geotechnics, H.R. Thomas, Ed., Thomas Telford Ltd., London, pp 43-69.

Rowe, R.K. (2007) "Advances and remaining challenges for geosynthetics in geoenvironmental engineering applications." Soils and Rocks (São Paulo), 30, Issue 10, pp 3-30.

Sample-Lord, K.M. and Shackelford, C.D. (2014) "Membrane behavior of unsaturated bentonite barriers." Geo-Congress 2014: Geo-Characterization and Modeling for Sustainability, M. Abu-Farsakh, X. Yu, and L.R. Hoyos, Eds., Geotechnical Special Publication 234, ASCE, Reston, Virginia, USA, pp 1900-1909.

Sample-Lord, K.M. and Shackelford, C.D. (2017a) "Membrane behavior of unsaturated sodium bentonite." Journal of Geotechnical and Geoenvironmental Engineering, 143, in press.

Sample-Lord, K.M. and Shackelford, C.D. (2017b) "Apparatus for measuring coupled membrane and diffusion behavior of unsaturated sodium bentonite." Vadose Zone Journal, 16, Issue 9.

Scalia, J. (2012) Bentonite-Polymer Composites for Containment Applications. Ph.D. Dissertation, University of Wisconsin-Madison, Madison, Wisconsin, USA.

Scalia, J., and Benson, C. (2011) "Hydraulic conductivity of geosynthetic clay liners exhumed from landfill final covers with composite barriers." Journal of Geotechnical and Geoenvironmental Engineering, 137, Issue 1, pp 1-13.

Scalia, J., Benson, C., Albright, W., and Smith, B. (2017) "Properties of barrier component in a composite cover after 14 years of service and differential settlement." Journal of Geotechnical and Geoenvironmental Engineering, 143, Issue 9, 04017055.

Scalia, J., Benson, C.H., Bohnhoff, G.L., Edil, T.B., and Shackelford, C.D. (2014) "Long-term hydraulic conductivity of a bentonite-polymer composite permeated with aggressive inorganic solutions." Journal of Geotechnical and Geoenvironmental Engineering, 140, Issue 3, 04013025.

Scalia, J. Benson, C.H, Edil, T.B., Bohnhoff, G.L., and Shackelford, C.D. (2011) "Geosynthetic clay liners containing bentonite polymer nanocomposite." Geo-Frontiers 2011: Advances in Geotechnical Engineering, J. Han and D.E. Alzamora, Eds., Geotechnical Special Publication 211, Dallas, TX, March 13-16, 2011, (CD-ROM) ASCE, Reston, Virginia, USA, pp 2001-2009.

Scalia, J., Bohnhoff, G.L., Shackelford, C.D., Benson, C.H., Sample-Lord, K.M., Malusis, M.A., and Likos, W.J. (2017) "Enhanced bentonites for containment of inorganic wastes by GCLs," Geosynthetics International, in review.

Schroeder, C., Monjoie, A., Illing, P., Dosquet, D., and Thorez, J. (2001) "Testing a factory-prehydrated GCL under several conditions." Proceedings, Sardinia 2001, 8th International Waste Management and Landfill Symposium, CISA Environmental Sanitary Engineering Centre, Cagliari, Italy, pp 187-196.

Shackelford, C.D. (2008) "Selected issues affecting the use and performance of GCLs in waste containment applications." Geosynthetics and Environment, Proceedings of the Geotechnical Engineering Conference of Torino (XXI Edition), M. Manassero, and A. Dominijanni, Eds., Politecnico di Torino, Torino, Italy, Nov. 27-28, 2007, Pàtron Editore, Bologna (CD-ROM; ISBN: 978-88-555-2953-2).

Shackelford, C.D. (2011) "Membrane behavior in geosynthetic clay liners." Geo-Frontiers 2011: Advances in Geotechnical Engineering, J. Han and D.E. Alzamora, Eds., Geotechnical Special Publication 211, Dallas, Texas, USA, March 13-16, 2011, (CD-ROM) ASCE, Reston, Virginia, USA, pp 1961-1970.

Shackelford, C.D. (2012) "Membrane behavior of engineered clay barriers for geoenvironmental containment: State of the art." GeoCongress 2012-State of the Art and Practice in Geotechnical Engineering, R.D. Hryciw, A. Athanasopoulos-Zekkos, and N. Yesiller, Eds., Geotechnical Special Publication 225, Oakland, California, USA, March 25-29, 2012 (CD-ROM), ASCE, Reston, Virginia, USA, pp 3419-3428.

Shackelford, C.D. (2013) "Membrane behavior in engineered bentonite-based containment barriers: State of the art." Coupled Phenomena in Environmental Geotechnics, M. Manassero, A. Dominijanni, S. Foti, and G. Musso, Eds., July 1-3, 2013, Torino, Italy, CRC Press/Balkema, Taylor & Francis Group, London, pp 45-60.

Shackelford, C.D. (2014) "The ISSMGE Kerry Rowe Lecture: The role of diffusion in environmental geotechnics." Canadian Geotechnical Journal, 51, Issue 11, pp 1219-1242.

Shackelford, C.D. (2017) "Coupled membrane and diffusion testing of active clays for barrier applications." International Workshop on Advances in Laboratory Testing and Modelling of Soils and Shales (ATMSS), A. Ferrari and L. Laloui, Eds., Jan. 18-20, 2017, Villars-sur-Ollon, Switzerland, Springer Intl. Publ. AD, Cham, Switzerland, pp 104-111.

Shackelford, C.D., Benson, C.H., Katsumi, T., Edil, T.B., and Lin, L. (2000) "Evaluating the hydraulic conductivity of GCLs permeated with non-standard liquids." Geotextiles and Geomembranes, 18, Issue 2-4, pp 133-161.

Shackelford, C.D. and Daniel, D.E. (1991) "Diffusion in saturated soil: I. Background." Journal of Geotechnical Engineering, 117, Issue 3, pp 467-484.

Shackelford, C.D. and Lee, J.-M. (2003) "The destructive role of diffusion on clay membrane behavior." Clays and Clay Minerals, 51, Issue 2, pp 187-197.

Shackelford, C.D., Malusis, M.A., and Olsen, H.W. (2003) "Clay membrane behavior for geoenvironmental containment." Soil and Rock America Conference 2003 (Proceedings of the joint 12th Panamerican Conference on Soil Mechanics and Geotechnical Engineering and the 39th U. S. Rock Mechanics Symposium), P.J. Culligan, H.H. Einstein, and A.J. Whittle, Eds., Verlag Glückauf GMBH, Essen, Germany, Vol. 1, pp 767-774.

Shackelford, C.D., Meier, A.J., Sample-Lord, K.M. (2016) "Limiting membrane and diffusion behavior of a geosynthetic clay liner." Geotextiles and Geomembranes, 44, Issue 5, pp 707-718.

Shackelford, C.D., and Moore, S.M. (2013) "Fickian diffusion of radionuclides for engineered containment barriers: Diffusion coefficients, porosities, and complicating issues." Engineering Geology, 152, Issue 1, pp 133-147.

Shackelford, C.D., and Sample-Lord, K.M. (2014) "Hydraulic conductivity and compatibility of bentonite for hydraulic containment applications." From Soil Behavior Fundamentals to Innovations in Geotechnical Engineering, M. Iskander, J. Garlanger, and M. Hussein, Eds., Geotechnical Special Publication 233 Honoring Roy E. Olson, ASCE, Reston, Virginia, USA, pp 370-387.

Shackelford, C.D., and Scalia IV, J. (2016) "Semipermeable membrane behavior in bentonite-based barriers: Past, present, and future." GEOVANCOUVER 2016, Oct. 2-5, 2016, Vancouver, Canada, Canadian Geotechnical Society, Richmond, British Columbia, Canada, paper 4173.

Shackelford, C.D., Sevick, G.W., and Eykholt, G.R. (2010) "Hydraulic conductivity of geosynthetic clay liners to tailings impoundment solutions." Geotextiles and Geomembranes, 28, Issue 2, pp 149-162.

Siebken, J.R., Swan, R. H. Jr., and Yuan, Z. (1997) "Short-term and creep shear characteristics of a needle punched thermally locked geosynthetic clay liner." STP 1308 Testing and Acceptance Criteria for Geosynthetic Clay Liners, L.W. Well, Ed., ASTM International, West Conshohocken, PA, USA, pp 89-102.

Trauger R., and Darlington J. (2000) "Next-generation geosynthetic clay liners for improved durability and performance." TR-220. Colloid Environmental Technologies Company, Arlington Heights, Illinois, USA, pp 2-14.

Trauger, R.J., Swan, R.H., and Yuan, Z. (1997) "Long-term shear strength behavior of a needle punched geosynthetic clay liner." STP 1308 Testing and Acceptance Criteria for Geosynthetic Clay Liners, L.W. Well, Ed., ASTM International, West Conshohocken, PA, USA, pp 103-120.

U.S. EPA (2001) "Geosynthetic clay liners used in municipal solid waste landfills." EPA530-F-97-002 (Revised December 2001). U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C.

Whitworth, T.M. and Ghazifard, A. (2009) "Membrane effects in clay-lined inward gradient landfills." Applied Clay Science, 43, Issue 2, pp 248-252.

Zanzinger, H. and Alexiew, N., (2000) "Prediction of long term shear strength of geosynthetic clay liners with shear creep tests." EuroGeo 2, 2nd European Geosynthetics Conference, A. Cancelli, D. Cazzuffi, and C. Soccodato, Eds., Patron Editore, Bologna, pp 567-571.

Zanzinger, H. and Alexiew, N., (2002) "Long-term internal shear testing on clay geosynthetic barriers." Clay Geosynthetic Barriers, H. Zanzinger, R.M. Koerner, and E. Gartung, Eds., Balkema, Lisse, The Netherlands, pp 111-117.

Zanzinger, H. and Saathoff, F. (2012) "Long-term internal shear strength of a reinforced GCL based on shear creep rupture tests." Geotextiles and Geomembranes, 33, Issue 8, pp 43-50.

Zanzinger, H. (2016) "Contribution to the long-term shear strength of a needle punched GCL." International Journal of Geosynthetics and Ground Engineering, 2, Issue 1, pp 1-7.

Zornberg, J. G., McCartney, J. S., and Swan, R. H. Jr. (2005) "Analysis of a large database of GCL internal shear strength results." Journal of Geotechnical and Geoenvironmental Engineering, 131, Issue 3, pp 367–380.