Water-Retention Behavior of Geosynthetic Clay Liners

Ryley A. Beddoe[1]; W. Andy Take[2]; and R. Kerry Rowe, F.ASCE[3]

Abstract: The hydration and subsequent hydraulic performance of geosynthetic clay liners (GCLs) depend on the water-retention curve (WRC) of the GCL. Because of the inherent difficulty in obtaining the WRC for these materials, limited data exists regarding the WRCs of GCLs in the literature. In this study, high-capacity tensiometers and capacitance relative humidity sensors were used to quantify the water-retention behavior of GCLs for four different GCL products that vary both in materials (woven and nonwoven geotextiles) and in fabrication detail (thermal treatment and needle-punching). The water-retention behavior was investigated under wetting and drying paths; we present results in terms of gravimetric and volumetric moisture content and bulk GCL void ratio. The WRCs of the different GCL products showed significant variation among wetting and drying curves, indicating that both needle-punching and thermal treatment have a significant effect on the swelling behavior of the GCL and its WRC. Theoretical equations were fit to the experimental data, establishing the parameters that can be used for numerical modeling of these four GCL products. **DOI: 10.1061/(ASCE)GT.1943-5606.0000526.**

CE Database subject headings: Clay liners; Landfills; Geosynthetics; Unsaturated soils.

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Introduction

A geosynthetic clay liner (GCL) consists of a bentonite layer that is bonded to one or more geosynthetics (e.g., sandwiched between two geotextiles by using needle-punched fibers or stitch bonding or to a geomembrane by using an adhesive). GCLs are commonly used as a hydraulic barrier (e.g., in a landfill and in mining applications: Rowe et al. 2004; Benson et al. 2010a, b; Gates and Bouazza 2010; Dickinson and Brachman 2010; Hornsey et al. 2010; Lange et al. 2010; Rosin-Paumier et al. 2010; Shackelford et al. 2010) because of the low hydraulic conductivity of the bentonite clay layer (Katsumi et al. 2008; Andrejkovicova et al. 2008; Guyonnet et al. 2009) and because of the composite action with geomembranes (Rowe et al. 2007; Brachman and Gudina 2008; Bouazza et al. 2008). GCLs are manufactured with nearly dry powdered or granular bentonite. However, this bentonite must hydrate upon GCL installation in the field for the low hydraulic conductivity of the bentonite to be realized. In the example of a GCL being used in a landfill liner application, this hydration usually will come from moisture transfer from the foundation soil once the GCL has been installed. Although GCL hydration is expected to occur after installation, there is a lack of data that quantify the unsaturated behavior of the GCL during this process. In particular, the constitutive relationship between suction and moisture content for GCLs, known as a water-retention curve (WRC), is particularly important because it defines the final equilibrium moisture content that a GCL will achieve during hydration.

Although hydration is essential for a GCL's ability to function as a hydraulic barrier, only a handful of publications have investigated the water-retention behavior of GCLs (Daniel et al. 1993; Barroso et al. 2006; Southen and Rowe 2007). These studies have focused on the water-retention behavior of a GCL either on a wetting or drying path. Both of these paths are important; the former quantifies GCL behavior during initial hydration, whereas the latter describes behavior during moisture loss and potential panel shrinkage. No data currently exist that describe both the wetting and drying WRC for a typical GCL product. One of the inherent reasons for this lack of data is the wide range of suctions that either need to be measured or must be imposed to quantify the WRC of these materials. The suction range of interest for GCLs ranges from approximately 1 kilopascal (kPa) when a GCL is saturated and blotted with a paper towel to 120 megapascals (MPa) at the typical as-delivered roll moisture content. Unfortunately, no one single suction measurement technique is capable of measuring this range. To overcome this limitation, a testing method using two different suction measurement techniques (high-capacity tensiometers and capacitive relative humidity sensors) was developed by Beddoe et al. (2010) to measure suction within GCL samples at low and high suctions.

The objective of this paper is to use the techniques developed by Beddoe et al. (2010) to investigate the complete WRC of four different geotextile-based GCL products under wetting and drying conditions. By testing different GCL products, we can highlight any effect that product materials or construction may have on the WRC. The overall aim of this work is to predict the parameters that can be used for numerical modeling of the unsaturated behavior of these four GCL products under both hydration and shrinkage field conditions.

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Materials and Methods

GCL Materials

Four GCL products with different manufacturing details and material properties were selected to investigate the effect, if any, of these differences on water-retention behavior. The first product selected, GCL1, is a thermally treated needle-punched GCL with a woven carrier and a nonwoven cover geotextile. GCL2 is a similar product, but it has a scrim-reinforced nonwoven geotextile as the carrier. These two products are fabricated by the same manufacturer, and they contain a fine granular bentonite ($d_{50} = 0.3$ mm). Products GCL3 and GCL4 are needle-punched GCLs manufactured by a different company, and they contain a coarser granular bentonite ($d_{50} = 0.7$ mm). Of these two products, GCL3 has a woven carrier and a nonwoven cover geotextile, whereas the cover and carrier geotextiles for GCL4 are both nonwoven. Dry sieve results performed on the two granulars are reported by Rowe et al. (2011). These four products were selected because they are the most commonly used types in North America and are currently being studied at the Queen's University Composite Geosynthetic Liner Experimental Site (e.g., Brachman et al. 2007) and in laboratory studies on moisture uptake (e.g., Rayhani et al. 2008) and shrinkage (e.g., Bostwick et al. 2010; Rowe et al. 2010, 2011). Further details on the specific properties of the four GCL products appear in Table 1.

Methods

Suction Measurement

Two different suction measurement techniques (high-capacity tensiometers and capacitive relative humidity sensors) were developed by Beddoe et al. (2010) to measure suctions within GCL samples to quantify the WRC over the full range of suctions applicable to these materials. For samples of matric suctions between 0 and 500 kPa, a high-capacity tensiometer was fitted with a five-bar air entry value ceramic filter, saturated and preconditioned following the techniques of Take and Bolton (2003), and used to provide a direct measurement of matric suction of GCL. This measurement was accomplished by making a small incision in the cover geotextile to gain access to the bentonite component of the GCL [Fig. 1(a)]. A thin layer of bentonite paste was then placed on the porous ceramic, and a 2-kPa seating load was applied to ensure full contact between the tensiometer and the bentonite within the core of the GCL during the minimum 12-h measurement period. This measurement duration was chosen because it satisfied the criterion for reaching equilibrium, defined in this study as the rate of change of measured matric suction being less than 1 kPa/h. For samples at suctions higher than 5,000 kPa, a Vaisala HMP45A relative humidity sensor was used to measure the temperature and equilibrium relative humidity of the airspace above the GCL sample [Fig. 1(b)], thereby enabling the calculation of total suction by using Kelvin's equation. Further details on both techniques can be found in Beddoe et al. (2010).

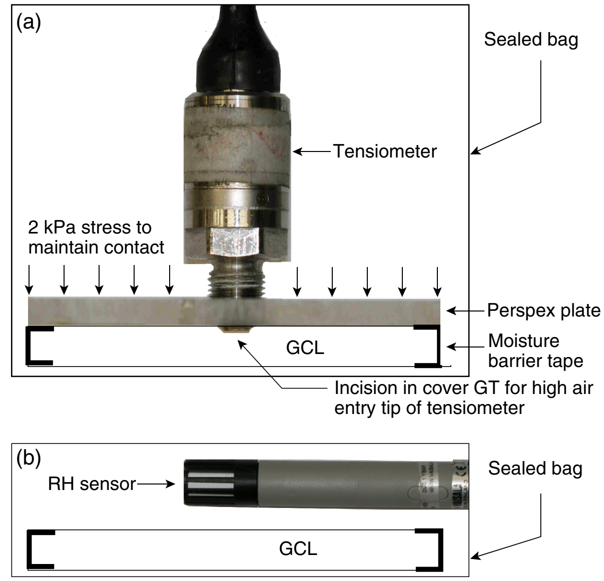

Fig. 1. Experimental methods for quantifying GCL suction using (a) high-capacity tensiometers for directly measuring matric suctions up to 500 kPa, and (b) capacitive relative humidity sensors for measuring total suctions greater than 5,000 kPa

Preparation of Drying Curve Specimens

To produce specimens on the drying curve for testing, a 400 mm × 250 mm sample of GCL was taken from the roll and was first hydrated by submerging the sample under water for one month.

Table 1. Geotextile Properties of GCL1-GCL4 as Typically Found off the Roll in the Field

			GCL1	GCL2	GCL3	GCL4
Properties	Average GCL mass per unit area (g/m^2)	Measured	4,679	4,241	5,084	4,944
		MARV	3,965	4,060	4,008	4,097
	Carrier geotextile	Type	W	NWS	W	NW
		Mass per unit area (g/m^2)[a]	123	260	125	233
	Cover geotextile	Type	NW	NW	NW	NW
		Mass per unit area[a] (g/m^2)	242	232	283	264
	Bentonite	Mineralogy[a] (percentage)	Montmorillonite 50–55	Montmorillonite 50–55	Montmorillonite 53–58	Montmorillonite 53–58
		As-delivered form	Fine granular	Fine granular	Coarse granular	Coarse granular
		Initial off-roll moisture content (percentage)[b]	11	6	12	9
	Structural	Needle-punched	Yes	Yes	Yes	Yes
		Thermally treated	Yes	Yes	No	No

Note: W = woven, NW = nonwoven, NWS = nonwoven scrim-reinforced, MARV = manufacturer's published minimum average roll value.
[a]Values from Bostwick et al. (2009).
[b]Rolls stored under dry laboratory conditions.

The hydration occurred under 2 kPa of applied normal stress to maintain similarity to samples prepared along the wetting curve (this will be discussed in more detail in this paper). When the large sample had hydrated, it was divided into 100 mm × 100 mm test specimens, and each specimen was placed on a drying rack and allowed to slowly lose moisture by evaporation until it reached its target moisture content, at which time the suction of the specimen was measured.

Beddoe et al. (2010) found that if no special precautions were taken, the preparations of drying curve specimens following this procedure were highly nonuniform in their moisture content, the bentonite at the edges of the specimen having a lower moisture content than the bentonite at the center of the specimen. To minimize the variation in moisture content and suction across the test specimen, it was necessary to eliminate the evaporation of moisture along the edges of the GCL. As a result, the loss of moisture from evaporation could occur only through the cover and carrier geotextiles. This was accomplished by sealing the edges of each drying curve specimen with an adhesive vapor barrier.

Preparation of Wetting Curve Specimens

To prepare GCL specimens on the wetting curve, specimens must start at the low as-delivered roll moisture content and be allowed to take up moisture until they reach progressively higher target moisture contents. The technique for hydrating GCL specimens along the wetting curve adopted in this study has been chosen to correspond as closely as possible to how GCL samples hydrate in the field—from direct contact with a moist soil foundation. Sealed 850 mm × 500 mm plastic containers were used to house 400 mm × 250 mm GCL samples placed in contact with a silty sand, prepared at a gravimetric moisture content of 21% (further details on the foundation soil appear in Brachman et al. 2007). A stress of 2 kPa was applied to the top of the GCL sample to ensure contact between the soil and GCL. The 2 kPa of normal stress was selected because it is low enough to remain representative of typical field conditions during hydration (i.e., it still allows near-free-swell conditions), but it has been shown to be great enough to be effective at maintaining contact during GCL hydration experiments and subsequently at increasing the rate of hydration (Rayhani et al. 2008). Each sample of GCL was then allowed to hydrate, with 100 mm × 100 mm square specimens harvested from time to time from the sample to produce incrementally higher target water contents.

GCL specimens were tested in a temperature-controlled laboratory at an average of 22°C. Thermal monitoring of temperatures within the laboratory indicates that all specimens were held to a ±0.2°C temperature fluctuation during the suction measurement phase of testing. At the conclusion of each test, the linear dimensions of the GCL specimen were taken with digital callipers to an accuracy of 0.1 mm. The thickness of the sample was measured with a laser scanner at an accuracy of ±0.05 mm (Brachman and Gudina 2008). A 2 kPa stress was applied to the GCL during the measurement of sample thickness to reduce errors associated with compression of the geotextile component and warping of the dried sample.

Gravimetric Water-Retention Curve Results

Gravimetric Drying Curve

Variation of Initial Moisture Content within a Single GCL Product

The initial state of GCL specimens prepared to investigate the drying curve is submerged hydration under 2 kPa of total stress.

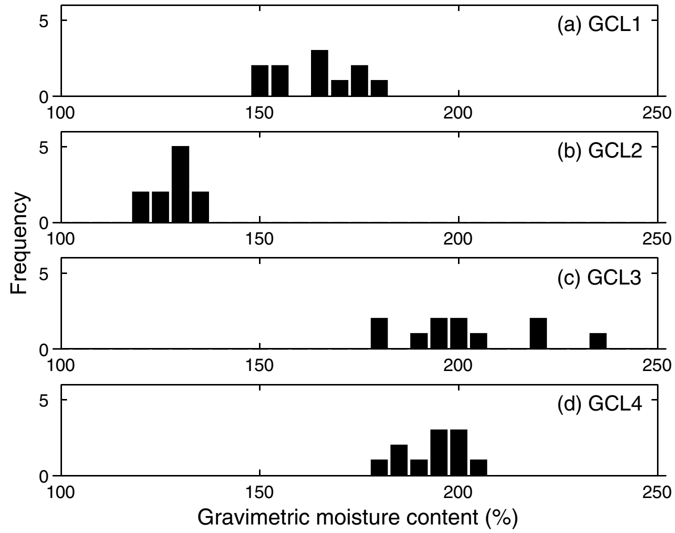

Fig. 2. GCL moisture contents after being submerged in water under 2 kPa stress for three weeks

To investigate the magnitude of variation to be expected along the drying curve, 11 specimens of each GCL product were allowed to hydrate under these controlled conditions. The resulting distribution of gravimetric moisture content achieved by each GCL product is reported in Fig. 2. These data indicate that the moisture content achieved by a given GCL product shows considerable variation, despite the measured suction values of all specimens being in the narrow band between 3 kPa and 10 kPa. Assuming that a normal distribution is valid for this data set, the mean and standard deviations of gravimetric moisture content for each GCL product are reported in Table 2. The 11 specimens taken for a given GCL product were all cut from the same 400 mm × 250 mm hydrated GCL sample. Had the GCL specimens been harvested from different sections of the same roll or between different rolls of the same product, the variation in gravimetric moisture content could be even greater than presented in this work. Nonetheless, because of this observed variation in gravimetric moisture content, one should anticipate that the level of variation in the gravimetric WRC for each GCL product will be higher than observed in soils, and as such will be in the form of a band rather than a unique line of closely spaced data points.

Variation of Initial Moisture Content between Different GCL Products

Fig. 2 indicates that the amount of variation in initial moisture content is a function of GCL product type. This is because of the specific GCL properties and method of manufacture of each product. The thermally treated, needle-punched, scrim-reinforced nonwoven GCL (GCL 2) had the smallest mean and standard deviation in hydrated moisture content of the four GCLs. The low moisture content arises from a lesser amount of swelling associated with hydration as a result of the higher confining stress imparted by the good attachment of the needle-punched fibers to the carrier geotextile. This higher confining stress arises from the nature of the carrier geotextile and the fusing of the needle-punched fibers to the carrier geotextile during thermal treatment. This observation is consistent with the findings of Lake and Rowe (2000b), who demonstrated that this product had a much lower hydrated void ratio than other products, resulting in better performance relating to both advection and diffusion (Lake and Rowe 2000a).

The role of the carrier geotextile can be assessed by comparing the results of GCL1 and GCL2 because both were thermally

Table 2. Gravimetric Water-Retention Curve Model Fit Parameters

GCL product	Moisture content at saturation		Fredlund and Xing parameters							
			Drying curve				Wetting curve			
	Mean	Standard deviation	a_f	n_f	m_f	ψ_r	a_f	n_f	m_f	ψ_r
	(percentage)	(percentage)	(kPa)			(kPa)	(kPa)			(kPa)
GCL1	166	10	73.4	1.60	0.88	943,600	32.6	0.46	1.76	924,875
GCL2	130	5	73.8	0.66	1.39	924,875	28.3	0.43	1.71	924,875
GCL3	205	16	55.5	1.22	1.05	943,559	17.1	0.59	1.46	934,170
GCL4	194	8	33.1	0.89	1.18	934,170	5.5	0.62	1.28	934,170

treated, but GCL1 had a woven slit-film carrier geotextile. This geotextile does not provide the same anchoring for the needle-punched fibers; consequently, it does not have an equally low hydrated moisture content (or bulk void ratio). The effect of thermal treatment can be assessed by comparing the results for GCL1 and GCL3, because both had a woven slit-film carrier but GCL1 was also thermally treated. In this case, the thermally treated product, GCL1, had a lower mean hydrated gravimetric moisture content and a lower standard deviation.

Because all of the initial moisture contents were within a narrow range of suctions between 3 kPa and 10 kPa, these data points can be visualized as the starting points on the drying curves for each GCL product. Because this variation is approximately normally distributed, the mean gravimetric moisture content at these conditions can be viewed as the point on the moisture content axis at which the drying curve is anchored. As a result, this hydration data indicates that the starting point for the gravimetric drying curve of a GCL will be highly product-specific.

Observed Drying Behavior

When the variation in initial hydrated gravimetric moisture content for the four GCL products had been quantified, additional specimens of hydrated GCL were slowly dried by evaporation through their cover and carrier geotextile. As each specimen reached its target moisture content, the suction in the GCL was measured by using the experimental procedures developed by Beddoe et al. (2010). For each GCL product, between 20 and 25 specimens were tested at suctions ranging from 10 kPa to 700 MPa to characterize the drying curve. The equilibrium values of gravimetric moisture content and suction obtained from these drying curve specimens are reported as solid circular markers in Figs. 3(a)–3(d) for GCL1 to GCL4, respectively. Although the generic term "suction" is used on the *x*-axis of Fig. 3(a), the tensiometer measured matric suction, whereas the relative humidity measurements yielded total suction. As a result, the total suction measurements include an extra osmotic component of suction. This osmotic component has been quantified in bentonitic barrier mixtures as approximately 1,000 kPa (Tang et al. 2002). However, because the vast majority of total suction measurements reported in Fig. 3 exceed 10 MPa, and mindful of the logarithmic nature of the suction axis, the fitted WRC function would not be significantly altered by this relatively small magnitude of osmotic suction. For this reason, and because the magnitude of this correction would have a significantly lower impact than the natural scatter in the moisture content data because of variations between samples of the same GCL, adjusting total suction values for osmotic suction was deemed irrelevant for the range of total suctions measured in this study.

A line of best fit through the drying curve points for each GCL, calculated by using the framework of Fredlund and Xing (1994), is presented in the results as a solid line. Also plotted on these figures is a vertical bar at the far left of the drying curve representing the range of gravimetric moisture content observed in the 11 nominally identical hydration specimens. These data points are represented this way to provide a visual representation of the inherent variation in gravimetric moisture content for each product. The height of the bar can therefore be interpreted as a measure of the expected width of the drying curve band for each product at low suctions. Comparing the drying curves for the four GCL products confirms that the gravimetric drying curve for GCLs is also highly product-specific. Although there exists a significant difference in the initial hydrated moisture contents, the shapes of the curves are broadly similar.

Gravimetric Wetting Curve

In contrast to the drying curve, in which drying specimens could be visualized as traveling along a WRC from left to right (i.e., from low suction values to high suction values), GCL specimens following the wetting curve travel from right to left (i.e., from high suction values to low suction values). The wetting data points for all four GCLs are represented by the open circles plotted on Figs. 3(a)–3(d). A line of best fit through the wetting curve points, based on the equation of Fredlund and Xing (1994), is presented as a dashed line. In the high-suction range, all four GCLs exhibit little measurable difference among data points on the wetting and drying curves. This is consistent with the findings of other researchers (e.g., Lu and Likos 2004) who have reported that the hysteresis of WRCs in soils is typically less pronounced near the residual degree of saturation. At lower suctions (1 kPa to 500 kPa), however, all four GCL wetting curves exhibited more hysteresis compared with that seen at high suction. In other words, a specimen following a wetting curve obtained a lower equilibrium gravimetric moisture content for the same suction than did a sample following the drying curve.

The magnitude of this hysteresis was a strong function of GCL type, with the thermally treated, scrim-reinforced GCL2 providing the least amount of hysteresis. This implies that the magnitude of hysteresis observed between the gravimetric wetting and drying curves is likely a result of the structure of the GCL rather than simply the result of the hysteresis effect seen in unsaturated soil materials, including bentonite clay.

The WRC reports equilibrium moisture contents at known suction values. Specimens on the wetting curve started at suctions on the order of 200 MPa and took hours to hydrate to suctions of 20 MPa, a week to reach a suction of 100 kPa, and approximately one month to reach a suction of 10 kPa. If these specimens were given significantly more time to hydrate, they would likely be subject to small increases in moisture content, albeit at a very slow rate. Mindful that the initial state of the drying curve samples was submerged hydration (i.e., the final state of a wetting path at a suction of 0 kPa suction), the Fredlund and Xing curve fit was made to be asymptotic to this value.

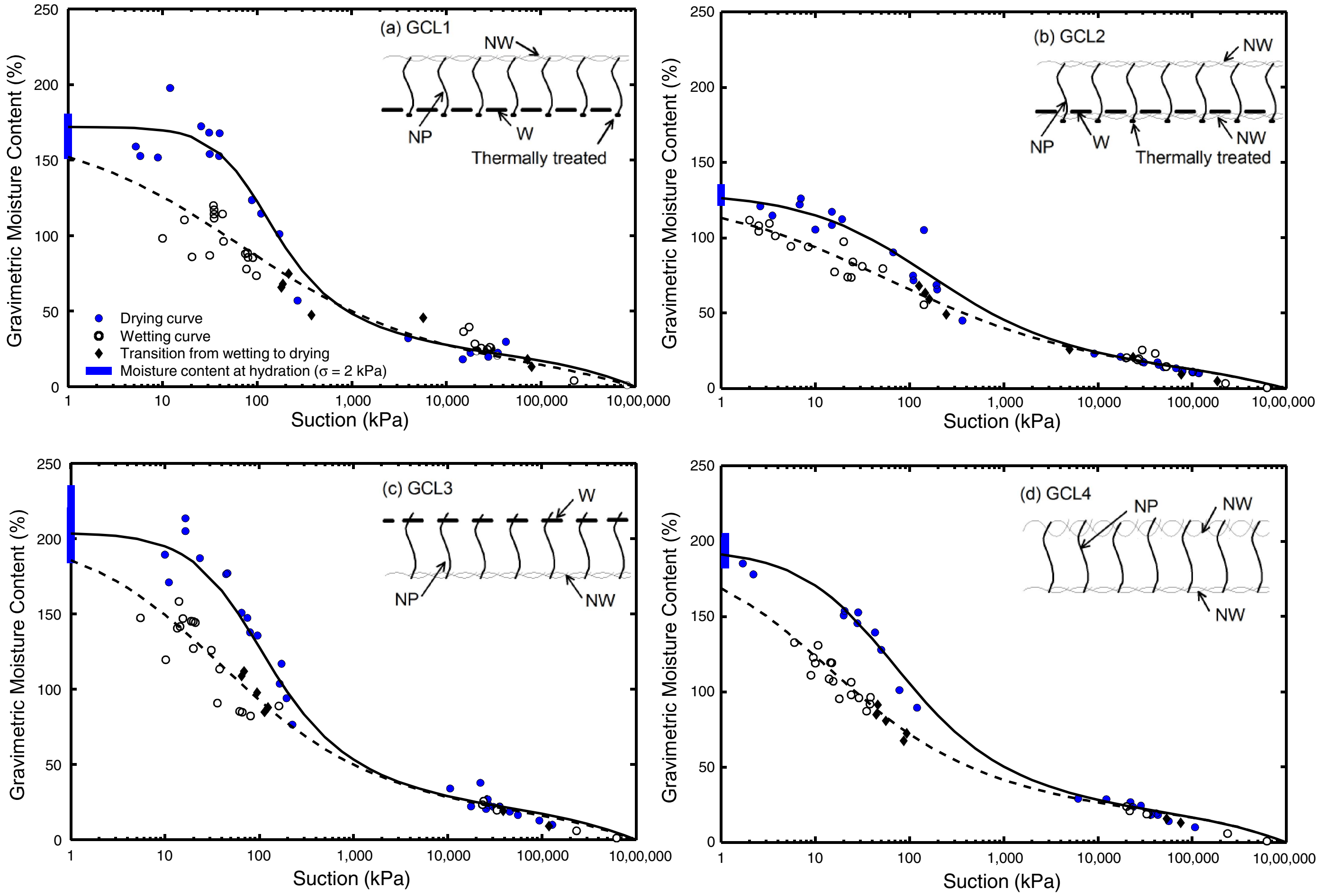

Fig. 3. Gravimetric water-retention curves for GCL1 to GCL4 (W = woven, NW = nonwoven, NP = needle-punched)

Transition from Gravimetric Wetting Curve to Subsequent Drying

In some cases, GCLs left exposed in the field and subjected to thermal cycles have experienced very little shrinkage (e.g., Gassner 2009), whereas in other cases (e.g., Thiel and Richardson 2005; Koerner and Koerner 2005; Thiel et al. 2006), field observations of GCL panel shrinkage imply that the GCL component of a composite liner may have been subjected to significant loss of moisture when the liner was left exposed. In this type of cyclic moisture behavior, the GCL would initially follow the wetting curve path as it hydrates from the foundation soil. If the geomembrane covering the GCL is exposed to solar radiation, a potential exists for large daily thermal cycles, particularly for black geomembranes, which are most commonly used (Pelte et al. 1994). The resulting downward thermal gradients could then cause the GCL to lose moisture and experience a drying episode.

To investigate this transition from the wetting curve to subsequent drying curve for GCLs, five to 10 specimens were tested under this scenario for each GCL type. These specimens were hydrated along the wetting curve for one month until achieving a suction of approximately 10 kPa. These specimens were then harvested and subjected to one-dimensional evaporation at 22°C through their cover and carrier geotextiles until they reached certain target moisture contents. The results are presented in Fig. 3 as solid diamonds. Interestingly, these results indicate that the gravimetric moisture content of a GCL that makes the transition from the virgin wetting curve to a drying episode follows a path that is indistinguishable from that of the virgin wetting curve. Similar behavior was seen in all four GCL products tested. This observed cyclic water-retention behavior of GCLs runs contrary to the typical scanning curve behavior seen in soils. This contrast in behavior between typical soils and GCLs suggests that the explanation for this unique behavior is somehow related to the structure of a GCL.

Volumetric Water-Retention Curve Results

Volumetric Drying Curve

The differences in mean gravimetric moisture content achieved by different GCLs under identical hydration conditions indicate that the gravimetric WRCs are highly product-specific and that the structure of the GCL greatly influences the amount of swelling. One strategy that could be adopted to try to normalize this data is to express the results in terms of volumetric moisture content. In so doing, we could use this experimental data to quantify the WRCs of the GCL products on a volumetric basis, as shown in Fig. 4.

The observed variation in volumetric moisture content of the hydrated GCL drying curve specimens before drying is plotted on the left side of each GCL product's volumetric WRC in Fig. 4. Whereas the mean gravimetric moisture content observed for the four GCL products hydrated under these conditions (2 kPa of normal stress) ranged from 130 to 225%, the magnitude of variation

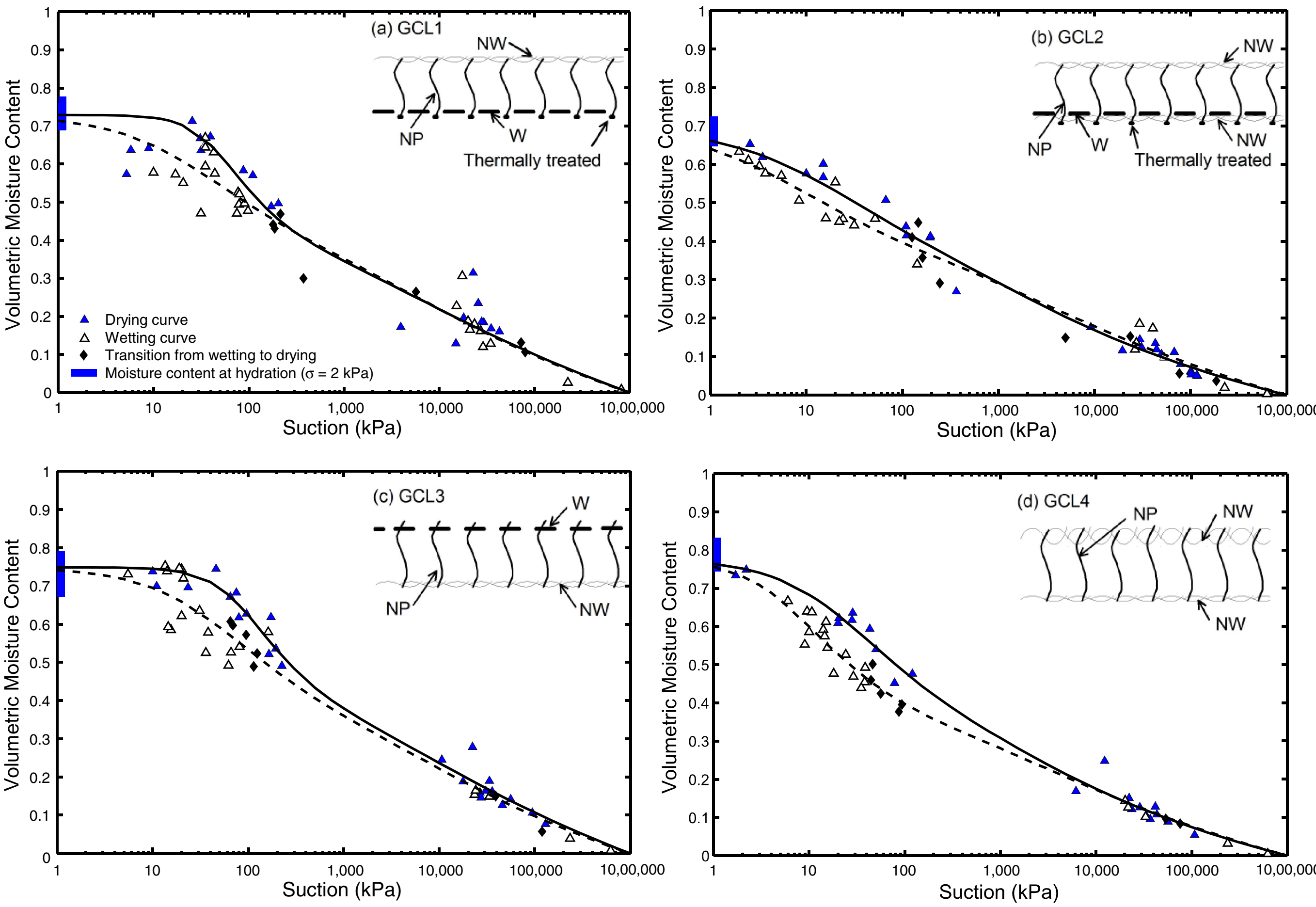

Fig. 4. Volumetric water-retention curves for GCL1 to GCL4 (W = woven, NW = nonwoven, NP = needle-punched)

between product types when expressed as a volumetric moisture content is significantly less; with the exception of GCL 2, the mean volumetric moisture contents of the GCLs lie within the range of 0.7–0.8. The lower mean volumetric moisture content of GCL2 (0.63) implies that the internal structure of the GCL (in this case, thermally treated and scrim-reinforced) is more efficient at constraining swelling than those of the three other products tested.

As the specimens of GCL were subjected to drying, the volumetric moisture content decreased for all GCL samples. Now that this drying curve is expressed in terms of volumetric moisture content, the curvature of the drying curve is significantly less than when presented in a gravimetric framework. In the present study, the kinematic boundary conditions associated with the evaporative drying of GCL specimens are under no horizontal edge restraint and are permitted to shrink vertically. As a result, the volumetric WRCs of Fig. 4 should be interpreted keeping in mind that both the volume of water and the volume of the GCL are decreasing with suction.

Volumetric Wetting Curve and Hysteresis

The water uptake behavior along the volumetric wetting curve of each GCL product is presented in Fig. 4 by open triangles. In contrast to the gravimetric WRCs, in which the wetting curve was substantially lower than the drying curve, the volumetric WRCs have a relatively minor degree of hysteresis between wetting and drying conditions. The differences among the moisture contents achieved at the same suction by specimens following the wetting and drying curves show that the wetting curve points generally reach a lower volumetric moisture content than their drying curve counterparts, with the magnitude of difference most apparent in the low suction range of each GCL.

Discussion

Bulk Void Ratio

We propose in this work that the magnitude of hysteresis observed between the gravimetric wetting and drying curves is a result of the structure of the GCL rather than solely the result of the hysteresis effect seen in unsaturated soils. Similarly, the surprising observations that samples following a wetting curve approximately go back down the wetting curve on subsequent drying (instead of following the drying curve) has been attributed to being related to the structure of the GCL. The validity of these hypotheses will be investigated in this section by using the concept of bulk GCL void ratio.

In their study on GCL swelling, Petrov et al. (1997) introduced the concept of a bulk GCL void ratio in an attempt to normalize their results of final GCL sample height against the variable mass of bentonite per unit area between GCL specimens. By using the mass and density of the various component materials, the volume of solids within a GCL can be calculated and a bulk void ratio defined as

$$e_B = \frac{V_{vb} + V_{vg}}{V_s} = \frac{V_t - V_s}{V_s} = \frac{H_{GCL} - H_s}{H_s} \quad (1)$$

in which V_{vb} = volume of voids in bentonite core, V_{vg} = volume of voids in the cover and carrier geotextile, V_s = total volume of solids, V_t = total volume of the GCL, H_{GCL} = GCL height, and H_s = height of solids in the GCL. H_s is defined as

$$H_s = H_b + H_g = \frac{M_{BENT}}{\rho_b(1 + \omega_o)} + \frac{M_{GEO}}{\rho_g} \quad (2)$$

in which H_b = height of bentonite solids, H_g = height of geotextile solids, M_{BENT} = reference mass of bentonite per unit in the GCL, ρ_b = density of bentonite solids, ω_o = initial bentonite moisture content, M_{GEO} = reference mass per unit area of geotextiles in the GCL, and ρ_g = density of polypropylene geotextile solids.

The observed relationships between the equilibrium bulk GCL void ratio at various suctions along the wetting and drying curves are plotted in Fig. 5. For specimens of GCL1 following a wetting path [open symbols in Fig. 5(a)], the bulk GCL void ratio slightly increased to a value of approximately 3.5 when wetted to a suction of 10 kPa. In contrast, specimens of GCL1 prepared for testing the drying curve have a bulk void ratio of approximately 5 at the same suction of 10 kPa. This implies that the samples prepared to test the drying curve have swollen to a much larger void ratio than the samples hydrated under contact with soil. This phenomena is the result of the different hydration histories of these two sets of GCL specimens.

For the drying curve specimens, the applied normal stress of 2 kPa proves insufficient to constrain swelling during submerged hydration (Lake and Rowe 2000b). As a result, Lake and Rowe (2000b) found, the large swelling pressures within the bentonite under similar near–free-swell conditions were sufficient to cause the needle-punching fibers to be pulled out of their geotextile anchors in certain GCL products. Because of this pull-out, the GCL achieved a greater height from swelling and consequently had a higher GCL bulk void ratio. For samples of GCL1 harvested along the wetting curve, the bulk void ratio begins as the as-delivered roll value [i.e., the bulk void ratio at the highest suction plotted in Fig. 5(a)]. As these samples of GCL1 followed the wetting path, the bulk void ratio increased slightly but did not reach the levels attained during near–free-swell conditions. This indicates that the hydration of GCLs along the wetting curve to suctions of 10 kPa does not subject the needle-punching fibers within GCL samples to the same magnitude of stress as is imposed during submerged hydration. This difference between the wetting and drying curve for bulk GCL void ratio is also found in Figs. 5(c) and 5(d) for GCL3 and GCL4, respectively.

In contrast, the thermally treated needle-punched, scrim-reinforced, nonwoven GCL (GCL2) did not experience the large increase in bulk GCL void ratio that was seen in other GCL products when they were hydrated under submerged conditions. This lower bulk void ratio is the result of a smaller amount of swelling because of the confining stress imparted by the good attachment of the needle-punched fibers to the carrier geotextile. This capacity for

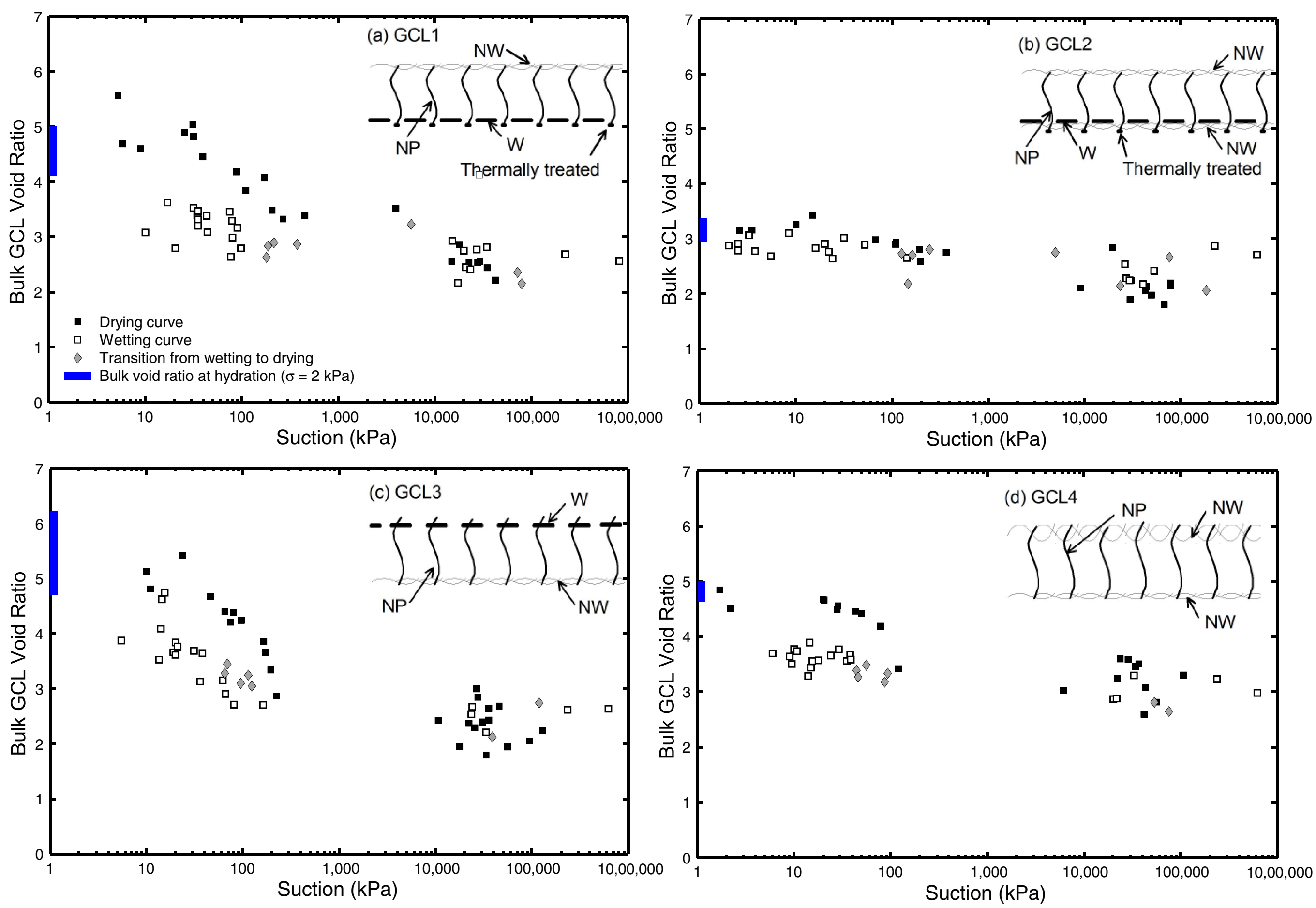

Fig. 5. Relationship between bulk void ratio and suction on wetting and drying paths for GCL1 to GCL4 (W = woven, NW = nonwoven, NP = needle-punched)

high confining pressures arises from the nature of the carrier geotextile and the fusing of the needle-punched fibers to the carrier geotextile during thermal treatment. As a result of this constant bulk void ratio between the wetting and drying curves, the magnitude of hysteresis observed between the wetting and drying branches of gravimetric WRC is minimized in this GCL. For the other GCL types tested (GCL1, GCL3, and GCL4), the loss of anchorage of the needle-punched fibers imposes the significant degree of hysteresis between the wetting and drying branches of gravimetric WRC.

The second observation attributed to the structure of the GCL relates to the path taken by wetting curve samples subjected to drying. As shown in Fig. 3, samples that initially follow a wetting curve will approximately go back down the wetting curve on subsequent drying. To investigate this phenomenon, we plotted the bulk void ratio of these cyclic drying specimens in Fig. 5 as diamond-shaped markers. These samples lie on the wetting curve; in other words, because these samples followed the wetting curve before being subjected to drying, they were never subjected to the large swelling pressures associated with the pull-out of needle-punched fibers. As a result, these drying specimens have more in common (i.e., a similar bulk GCL void ratio) with the wetting curve than they do with the drying curve specimens, which have been damaged by pull-out. It is therefore entirely reasonable that these samples will follow a drying WRC that closely follows the original wetting WRC for each GCL type.

Observations of the impact that the GCL bulk void ratio has on the gravimetric WRC raise significant questions regarding the appropriate choice of curve to model field behavior. At first glance, it seems apparent that modeling of the initial hydration behavior should require the wetting curve with any subsequent drying behavior (if the composite liner is subjected to harsh exposure conditions) following a scanning curve to the drying curve. However, the observed changes in the bulk GCL void ratio for certain GCL products under near–free-swell conditions indicate that a more representative curve for modeling shrinkage would be a drying path that closely follows the wetting curve. This observation has been made for GCL samples that have been subjected only to one cycle of wetting and drying and have not experienced cation exchange. Under long-term field exposure, it is possible that seasonal wetting and drying may also be accompanied by cation exchange within the bentonite of the GCL, resulting in a change in swelling (and therefore the water retention) characteristics of the GCL. Further research is required to understand the magnitude of cation exchange effects on the WRC of GCLs.

Comparison to Published Data

To be applied as a constitutive relationship within a numerical model, a continuous curve must be derived from the equilibrium moisture content and suction values observed in the test specimens. Many forms of equations have been developed to fit laboratory data points on a WRC (e.g., Brooks and Corey 1964; van Genuchten 1980; Lloret and Alonso 1985; Fredlund and Xing 1994). The primary difference among these equations is the degree of flexibility of the fitting curve's shape. For the GCL WRCs defined in the present study, the curve fit proposed by Fredlund and Xing (1994) provided a good fit at high suctions because this model forces the gravimetric moisture content to zero at a suction of 1,000 MPa. This imposed shape of the WRC at high suctions is consistent with the laboratory data obtained from GCL specimens at high suctions (e.g., Fig. 3). The Fredlund and Xing equation is given by

$$\theta = \theta_s \left[1 - \frac{\ln(1 + \psi/\psi_r)}{\ln(1 + 10^6/\psi_r)}\right] \left[\frac{1}{\ln(e + (\psi/a_f)^{n_f}}\right]^{m_f} \quad (3)$$

in which θ = volumetric water content (m^3/m^3); θ_s = saturated water content (m^3/m^3); ψ = capillary pressure (suction) (kPa); ψ_r = residual capillary pressure (suction) (kPa); and a_f (kPa), n_f, and m_f are fitting parameters. Values for the Fredlund and Xing (1994) parameters are included in Table 2 for the gravimetric wetting and drying curves. The magnitude of the fitting parameters is relatively consistent among GCL types, with the exception of that of the parameter that defines the saturated gravimetric moisture content. This indicates that the shapes of these WRCs are broadly similar, but it demonstrates gravimetric WRC's high dependence on the susceptibility of a given product to the pull-out of needle-punched fibers. Curve fitting was also undertaken for the wetting and drying curves, expressed in terms of volumetric water content. These parameters are listed in Table 3.

A comparison with the water-retention behaviors published in the literature is presented in Fig. 6 in terms of gravimetric moisture content observed along a drying path. This figure presents the published relationships between gravimetric moisture content and suction for three different bentonite clays (MX-80, Kunigel, and FEBEX) as open markers, and it presents published results for GCL products as solid markers. These results indicate that the gravimetric WRCs compare well with the published data for pure bentonite at high suctions. As shown in Fig. 6, the relationship between gravimetric moisture content and suctions is similar for all GCL products and pure bentonites at suctions in excess of 10 MPa. This implies that the behavior on this portion of the curve is dominated by the bentonite component of the geocomposite. In contrast, the relationships between gravimetric moisture content and suction for pure bentonite and GCLs in the low suction regions (less than 1,000 kPa) diverge significantly. In this region, the effect of the normal confining stress provided by the needle-punched fibers dominates.

The drying gravimetric WRCs quantified for the four products investigated in this study compare well with the published data from previous studies. Southen and Rowe (2007) tested the drying curve of two GCL products, GCL-SR1 and GCL-SR2. Product

Table 3. Volumetric Water-Retention Curve Model Fit Parameters

	Moisture content at saturation		Fredlund and Xing parameters							
			Drying curve				Wetting curve			
	Mean	Standard deviation	a_f	n_f	m_f	ψ_r	a_f	n_f	m_f	ψ_r
GCL product	(m^3/m^3)	(m^3/m^3)	(kPa)			(kPa)	(kPa)			(kPa)
GCL1	0.73	0.03	36.6	2.01	0.36	2,269	13.1	0.84	0.51	2,559
GCL2	0.70	0.02	7.2	0.67	0.63	938	2.1	0.73	0.51	637
GCL3	0.74	0.03	67.1	1.80	0.40	3,489	25.5	0.92	0.55	2,386
GCL4	0.78	0.02	13.6	0.93	0.59	1,083	4.3	1.23	0.48	411

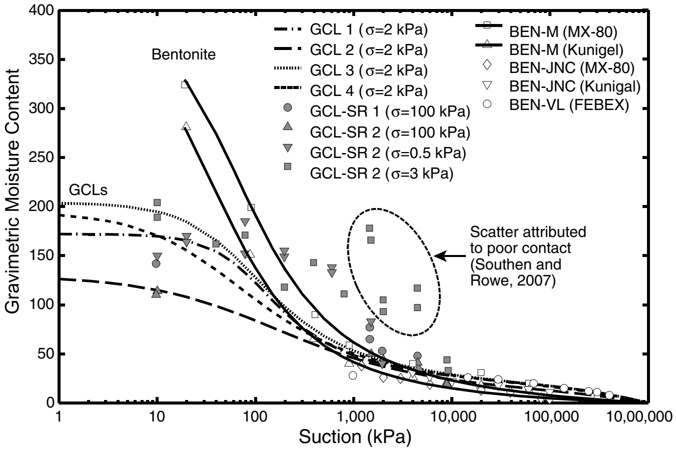

Fig. 6. Comparison of drying path water-retention curves obtained in the present study, with published results of Southen and Rowe (2007) (GCL-SR) and the bentonite data of Marcial et al. (2002) (BEN-M); Japan Nuclear Cycle Development Institute (JNC) (2000) (BEN-JNC); and Villar and Lloret (2004) (BEN-VL)

GCL-SR1 consisted of a needle-punched, thermally treated, woven slit-film carrier and a nonwoven cover geotextile containing granular bentonite. Product GCL-SR2 contained powdered bentonite and was thermally treated, and its nonwoven cover geotextile was impregnated with bentonite. These GCLs were then subjected to different overburden pressures ranging from 0.5 kPa to 100 kPa, in an effort to investigate the effect of overburden pressure. The points to the right of the main GCL retention curves are discounted by Southen and Rowe (2007) because they are thought to be the result of measurement error from lack of contact between the GCL and the porous membrane of the pressure plate apparatus.

The wetting results of tests performed on a GCL fabricated of bentonite and adhesively bonded to a high-density polyethylene geomembrane (GCL-D and GCLB-4), reported by Daniel et al. (1993) and Barroso et al. (2006), respectively, are shown in Fig. 7. The results differ, especially at higher water contents. This is a reflection of the water-soluble glue beginning to dissolve, allowing for much greater swelling to occur. The results from GCL-D and GCLB-4 line up well with the bentonite results, indicating that the wetting curve for high-density polyethylene (HDPE) adhesive bentonite GCLs resembles that of bentonite because of a lack of confinement that counteracts the swelling pressure.

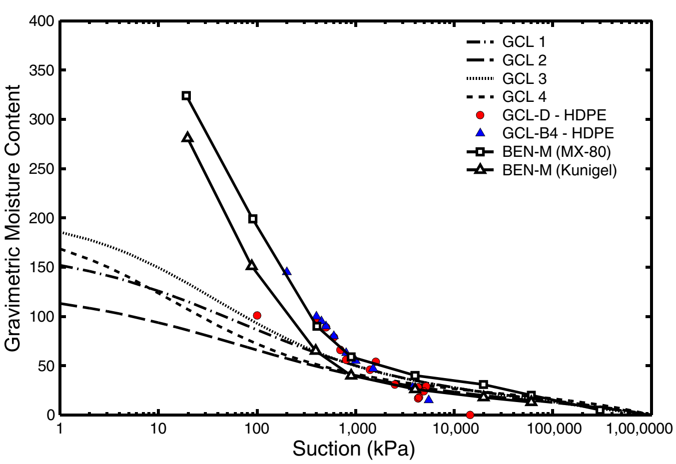

Fig. 7. Comparison of wetting path water-retention curves obtained in the present study, with published results of Daniel et al. (1993) (GCL-D) and Barroso et al. (2006) (GCL-B4) and the bentonite data of Marcial et al. (2002) (BEN-M)

Conclusions

We have presented the results of an experimental study investigating the effects of different manufacturing details and material properties of GCL products on their water-retention behavior. Gravimetric and volumetric WRCs were established under wetting and drying conditions for four GCL products under 2 kPa normal stress. Specimens of a single GCL type presented on the gravimetric drying curve showed a significant variation in gravimetric moisture content at the same equilibrium suction. This implies that because of the inherent variability of GCLs, the WRC for each product should be interpreted as a band of possible values centered around the mean drying curve. The magnitude of variability appears to be related to the method of manufacture and the degree to which the fibers are interlocked. The least variability was in the thermally treated GCL with a scrim-reinforced carrier geotextile (GCL2), followed by GCL4, which had a nonwoven carrier, then by GCL1, which had a woven but thermally treated carrier, and finally by GCL3, which had only a woven carrier and gave the greatest variability.

The amount of hysteresis between the gravimetric wetting and drying curves was a strong function of GCL type, with the thermally treated, needle-punched, scrim-reinforced nonwoven GCL (GCL2) providing the least amount of hysteresis. This observation implies that the magnitude of hysteresis observed between the gravimetric wetting and drying curves is largely a result of the structure of the GCL rather than simply a result of the hysteresis effect seen in unsaturated soil materials, including bentonite clay.

This phenomenon was further investigated by studying the relationship between bulk GCL void ratios, with suction for specimens prepared along both wetting and drying curves. These results indicate that the large swelling pressures to which the drying curve specimens were subjected under their initial near–free-swell conditions were sufficient to cause some of the needle-punching fibers to pull out of their geotextile anchors in certain GCL products. Because of this pull-out, the GCL achieved a greater height from swelling, and consequently it had a higher GCL bulk void ratio. As a result, the amount of hysteresis between the gravimetric wetting and drying curves was found to be a function of the GCL's ability to resist these swell pressures. The amount of hysteresis was minimal in the GCL product with the best anchorage (GCL2), and it was significant in the GCL products that experienced pull-out of needle-punched fibers on swelling (GCL1, GCL3, and GCL4).

The differences in GCL bulk void ratio on samples following a wetting and drying path had important considerations for modeling shrinkage phenomena. Tests performed on GCL specimens that had originally been following a wetting curve but were then subjected to drying before saturation was reached dried along a path similar to that of their original wetting curve. The explanation for this behavior was in the bulk GCL void ratio data. Because these samples followed a wetting curve before being subjected to drying, they were never subjected to the large swelling pressures associated with the pull-out of needle-punched fibers. As a result, these drying specimens behaved much like the specimens at a similar bulk void ratio (i.e., specimens prepared along the wetting curve). This observation implies that in the case of a GCL subjected to shrinkage in the field, the more representative curve for modeling shrinkage would be a drying path that closely follows the wetting curve, as long as no cation exchange has occurred within the bentonite of the GCL. Further research is required to quantify the implication of cation exchange on the long-term cyclic water-retention behavior of GCLs.

Finally, the water-retention behavior reported in this study is for the case of exposed composite liners characterized by low normal stress (2 kPa) and significant vertical swelling upon hydration. At higher confining stress, the magnitude of swelling during hydration will be considerably lower which will result in significant differences in the water-retention behavior, particularly at low suctions.

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