Experimental investigation of a heterogeneous GCL model

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ABSTRACT: Hydraulic conductivity, a property initially conceived as an intrinsic property of a homogenous porous media, is commonly used to describe the performance of Geosynthetic Clay Liners (GCLs). In engineering practice, it is also used as an index value to specify a minimum GCL performance threshold for project requirements. GCLs, however, are heterogeneous materials comprised of synthetic fibers and bentonite clay at various concentrations along a given cross section. A conceptual model of a GCL as layers of bentonite clay contaminated with synthetic fibers was conceived and tested. By considering heterogeneity, the model allows a more thorough Darcian analysis of GCL design performance to be incorporated into composite liner leakage calculations, transmissive flow over GCLs, and transmissive flow through GCL overlaps. A new permeameter configuration was used to measure transmissive flow through the non-woven geotextile component of a needle punched GCL.

Keywords: *GCL, geosynthetic clay liner, hydraulic conductivity, transmissive flow, permeameter*

1 INTRODUCTION

The use of hydraulic conductivity to describe GCL performance is commonplace in part because it offers a description of flow which is normalized to hydraulic head. This allows designers to compare performance between other geosynthetics as well as other systems such as compacted clay liners (CCLs). It is important, however, to respect the limitations of hydraulic conductivity as it applies to a GCL. An instructive way to do this is to observe the words of Henry Darcy: ‘‘It thus appears that for sand of comparable nature, one can conclude that flow volume is proportional to the head loss and inversely related to the thickness of the layer traversed’’ and further defining hydraulic conductivity as “a coefficient dependent on the permeability of the layer” (Brown 2002). Hydraulic conductivity has proven to be a useful coefficient for materials beyond the range of “sand of a comparable nature”, however swelling bentonite clays, polymer modified clays, and fiber reinforced GCLs push Darcy’s coefficient to its useful limit.

An important feature of hydraulic conductivity is the assumed homogeneity of the material. GCLs, of course, are not entirely homogeneous. Most GCLs today, like the ones shown in Figure 1, are made from the needle punch method of manufacture. Needle punching gives the material shear strength by linking the upper and lower (aka cover and carrier) geotextiles with synthetic fibers. The fibers within the GCL can be thought of as contamination of the bentonite clay. The purpose of the fibers is structural only. The fibers occupy space otherwise occupied by swelling, self-healing and highly impermeable bentonite clay. There are documented cases of fiber bundles that penetrate the bentonite layer and leave a rather dramatic pore space for preferential flow through the GCL (Scalia and Benson 2010). Expanding on the concept of a GCL as bentonite clay contaminated with fibers, one can theorize that there would be a dramatic change in hydraulic performance as the fiber to bentonite ratio went from 0% (pure bentonite clay) to 100% (fibers only).

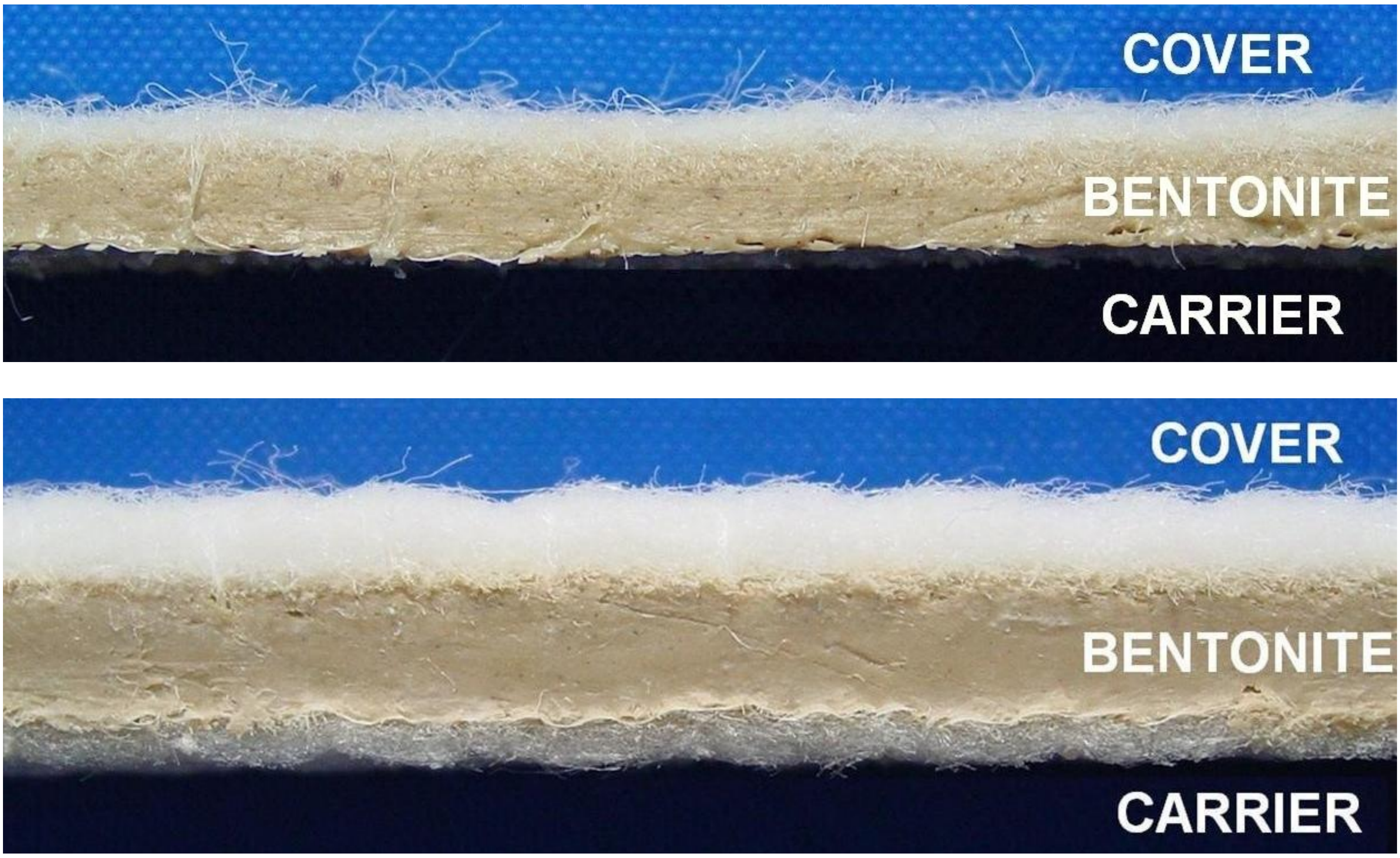

Figure 1:Two types of hydrated GCL in profile featuring woven and nonwoven geotextiles.

The testing approach seeks to observe the heterogeneity of GCLs experimentally using novel testing equipment. The aims of the experiments are not only to improve understanding of the fundamental properties of GCLs, but to also introduce a practical test method to ensure construction and manufacturing quality assurance of GCL overlap joins.

2 MATERIALS AND METHODS

ASTM D5887 entitled, *Standard Test Method for Measurement of Index Flux Through Saturated Geosynthetic Clay Liner Specimens Using a Flexible Wall Permeameter*, describes the standard method used to measure the hydraulic conductivity of GCLs (ASTM D5887-16). This method can be modified in a simple but significant way. By reorienting the GCL specimen to a vertical orientation, the transmissive flow through the GCL can be measured. To achieve this orientation within the standard test equipment, an HDPE cylinder is introduced. The dimensions of the cylinder are tailored to fit into the standard permeameter equipment with a diameter of 100mm and a height of 140mm. A wide cut is made along the center axis of the cylinder. The width of the cut is designed to match the thickness of the rectangular GCL specimens which are to be placed between the two halves of the cut cylinder as seen in Figure 4. The standard porous stone and filter paper are placed on the top and bottom of the cylindrical components and the entire setup is wrapped in a latex sleeve. If two GCL specimens are placed in between the halves, transmissive flow through the overlapping specimens can be measured.

The GCL used in these experiments, named GCL1, consists of a polymer modified sodium bentonite powder needled between a woven carrier geotextile and a non-woven cover geotextile. The typical properties of the GCL are outlined in Table 1. It should be noted that GCL1 is manufactured with additional bentonite impregnated along the outer 300mm of the side edges of the roll to achieve ensured sealing in this area. The overlapping specimens tested for this paper are taken from this area. Along the ends of rolls, manufacturers typically recommend additional bentonite (in the form of powder, granules or paste) to be placed during installation. The end of roll overlap treatment is not evaluated in this paper.

Table 1:Typical properties of GCL1

Property	Test Method	Units	Typical Value
Hydraulic Conductivity	ASTM D5887	m/s	1.9 x 10^{-11}
Bentonite Particle Size	AS 1289-3.6.2	% ≤ 0.5µm	≥ 55
Swell Index	ASTM D5890	mL/2g	≥ 24
Fluid Loss	ASTM D5891	mL	≤ 15
Cover Nonwoven Geotextile Mass per Unit Area	AS 3706.1	g/m^2	270
Bentonite Mass per Unit Area @ 0% Moisture Content	ASTM D5993	g/m^2	4,500
Carrier Geotextile Mass per Unit Area	AS 3706.1	g/m^2	110
Total GCL Mass per Unit Area @ 0% Moisture Content	ASTM D5993	g/m^2	4,880

A diagram of the modified permeameter can be seen in Figure *2*. In the modified permittivity cell with vertical orientation, the standard method and procedures can be maintained, only the geometry and specimen orientation change. The standard confining pressure of 35kPa was used.

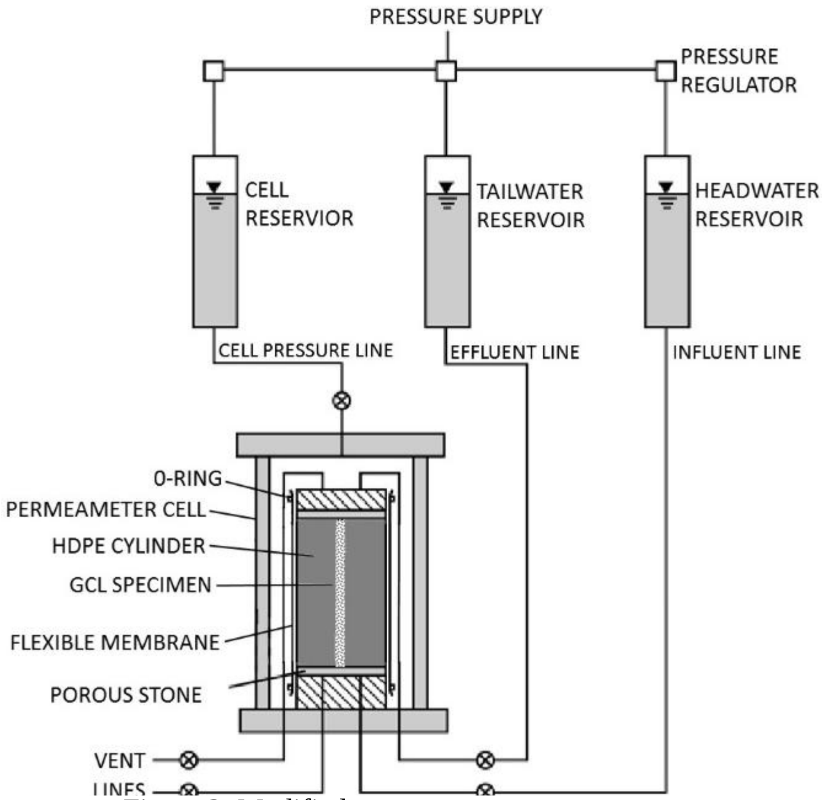

Figure 2: Modified permeameter test apparatus

Following the ASTM standard for the falling head test in which the influent and effluent reservoirs have the same cross-sectional area, we can calculate hydraulic conductivity as follows:

$$k_T = \frac{aT}{2At} ln\left(\frac{h_1}{h_2}\right) \quad (1)$$

$Where$:
$k_T = hydraulic\ conductivity, m/s$
$T = thickness\ of\ clay\ component, or\ height\ of\ cylinder\ in\ the\ modified\ cell, m$
$A = cross\ sectional\ area\ of\ specimen, or\ diameter\ times\ GCL\ thickness\ for\ modified\ cell, m^2$
$t = elapsed\ time\ between\ determination\ of\ h_1\ and\ h_2, s$
$h_1 = head\ loss\ across\ specimen\ at\ time\ t_1, m$
$h_2 = head\ loss\ across\ specimen\ at\ time\ t_2, m$

This equation assumes constant flow through a rectangular cross section of a homogeneous material. The homogeneous assumption is an approximation. There are sections within the rectangular profile which have varying concentrations of fiber mixed in with the bentonite. These conditions could allow for uneven exposure to moisture and uneven swelling further deviating from a homogeneous assumption. In the case representing an overlap where two GCLs are sandwiched within the cylinder and bentonite paste is installed along the walls of the cylinder, the total thickness of 2x GCLs was used for cross sectional area thickness in Eq.(1). In this case, the homogeneous assumption stretched further. This is visually evident in Figure 3 as an interface of porous geosynthetic fibers can be seen.

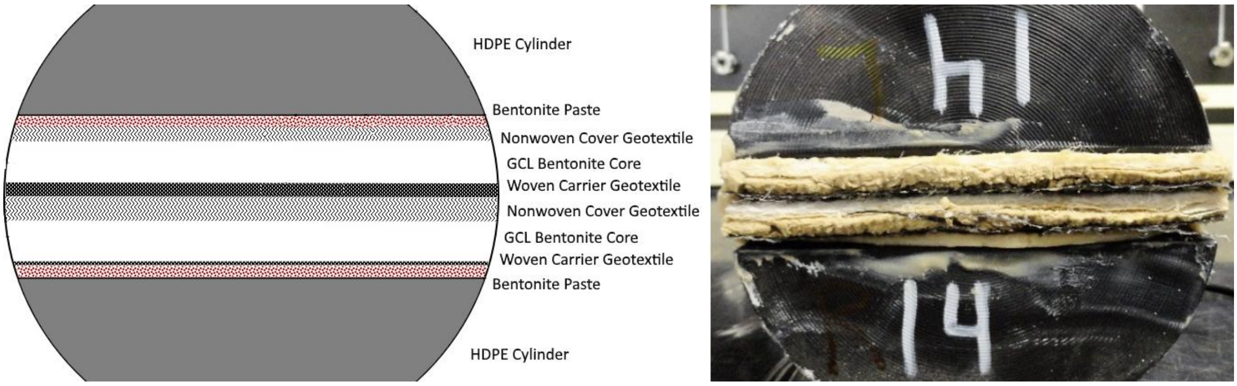

Figure 3: Overlapping GCL specimens within the HDPE Cylinder.

The modified permeameter setup was used to test 3 different scenarios which are depicted in Figure 4.

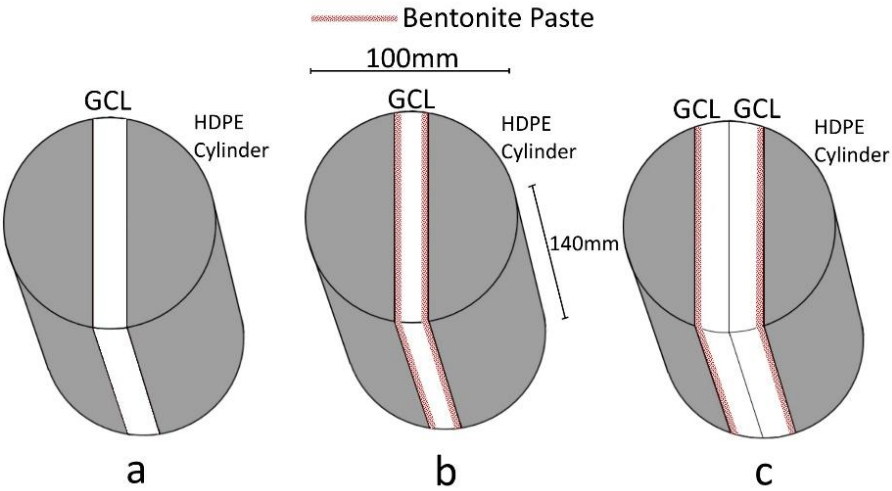

Figure 4: GCL specimens installed in the modified permeameter. a) GCL specimen sourced centrally from the roll. No additional paste or bentonite along the GCL-cylinder wall interface. b) GCL specimen sourced centrally from the roll with bentonite paste along both GCL-cylinder walls. c) 2x GCL overlap samples sourced from the overlap zone of the GCL. This GCL features additional powdered bentonite impregnated into the nonwoven cover geotextile component to improve sealing in this area.

One challenge with these measurements is the method of accounting for flow along the GCL-cylinder wall interface. This flow was found to be non-trivial in comparison to the transmissive flow between two GCL overlapping sections. Bentonite paste was used to seal this interface between the fibrous GCL surface and the HDPE cylinder. Multiple tests were performed with a single GCL specimen to understand and account for the flow through the GCL core and along the HDPE cylinder wall interface.

3 RESULTS AND DISCUSSION

3.1 *Overview of results and observations*

The following noteworthy observations were made:

- The in-plane hydraulic conductivity of the GCL with its fibrous components covered in bentonite paste can be more than one order of magnitude greater than the cross-plane hydraulic conductivity of the GCL.

- In cases where no paste is applied, the bentonite within the GCL does swell into the fibrous components of the GCL reducing the hydraulic conductivity significantly as predicted (Koerner 2005).
- A Darcian model which makes use of the transmissive (i.e. in-plane) hydraulic conductivity of the GCL can be useful to compare flows expected from GCL overlaps with the parent GCL.
- The flow contribution from the overlap is non-trivial. It can be shown that hydraulic conductivity within a GCL can fluctuate by 1 or 2 orders of magnitude depending on the orientation at which it is measured, i.e. in-plane or cross-plane.

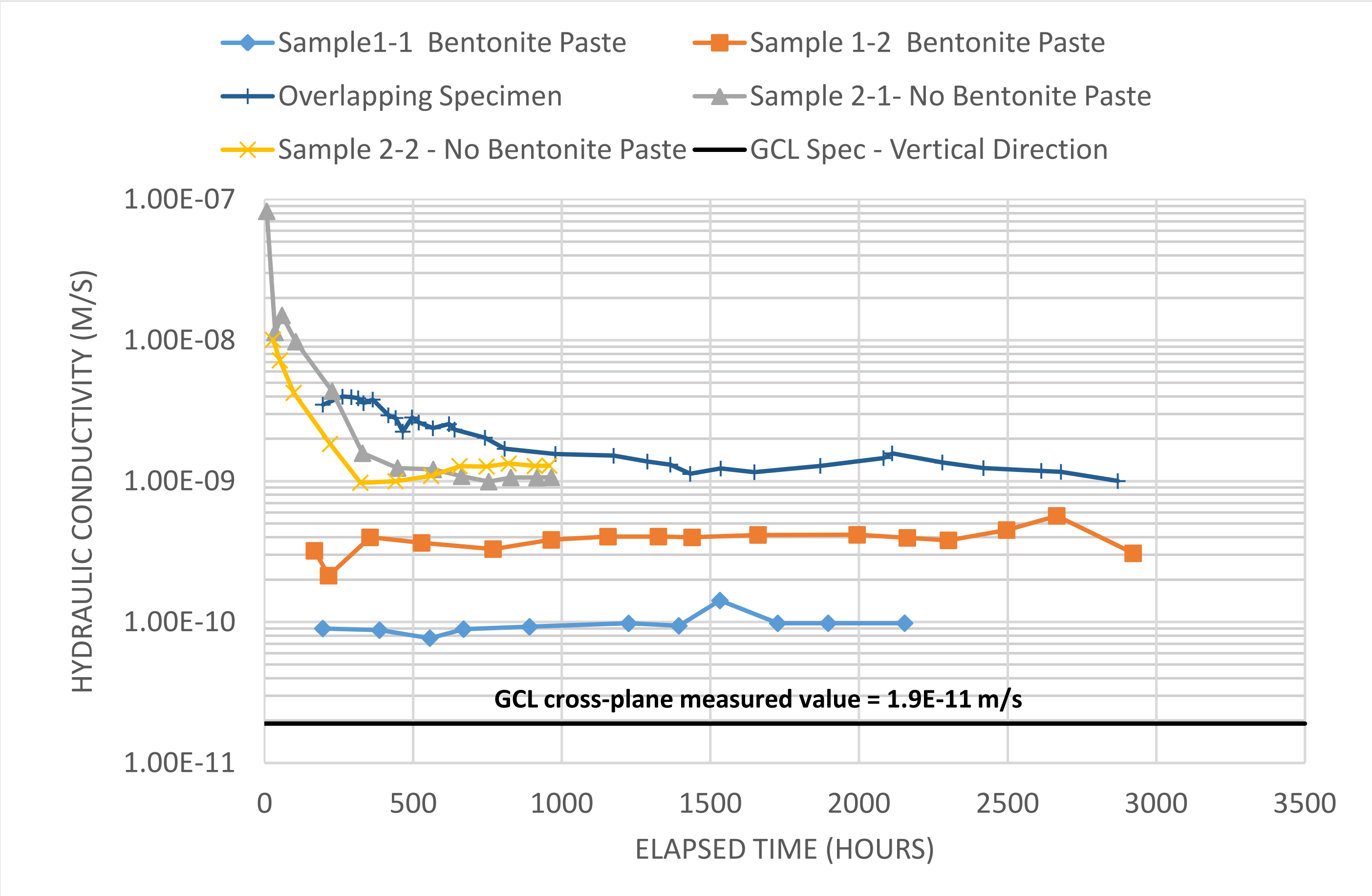

Figure 5:Plot of Hydraulic Conductivity results over time.

3.2 *Considerations for GCL overlap flow contributions*

It was observed that the hydraulic conductivity measured from Figure 4a is approximately equivalent to the hydraulic conductivity measured from Figure 4c and the flow contribution from the bentonite core is comparably small. In other words, the results shown in Figure 5 suggest that transmissive flow through a GCL overlap is approximately equivalent to the flow through the single GCL specimen without bentonite paste. This is logical because the same components and flow paths, normalized for thickness, are all present: a cover geotextile, a carrier geotextile and a bentonite core.

It is proposed that the transmissive flow through the overlap can be approximated using Darcy's law through a rectangular cross section of 1x GCL thickness as shown in Figure 6.

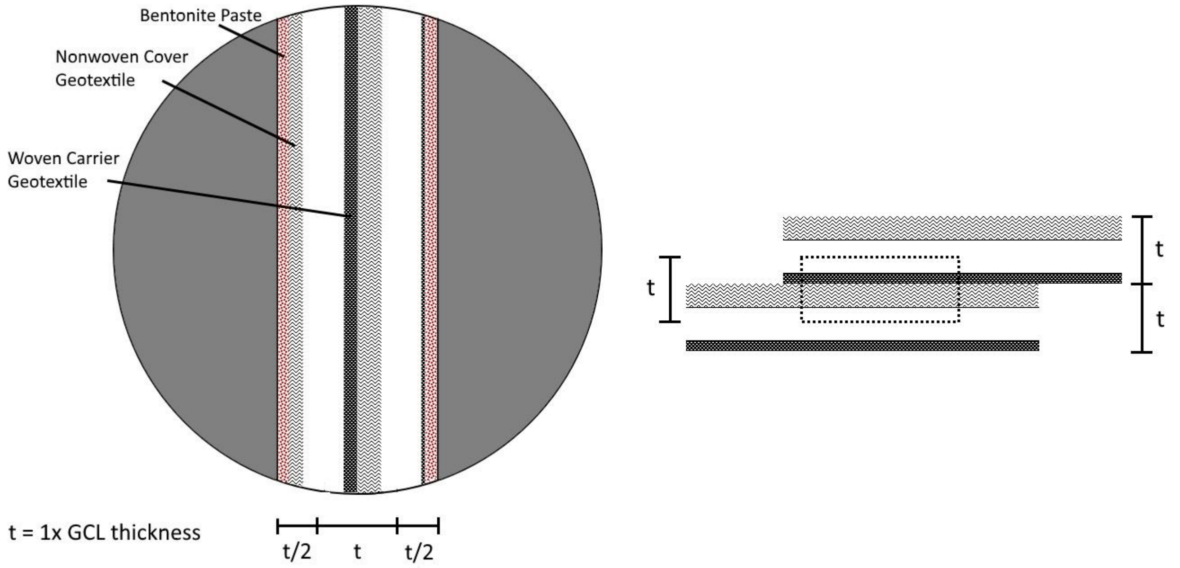

Figure 6: GCL overlap detail within the modified permeameter (left) and an overlap cutout with dimension details used in analysis (right).

Observing Darcy's law, for every meter length of GCL roll we can calculate the flow rate in m^3/s from the parent GCL roll as follows:

$$q_{roll} = k_{cp}\frac{h}{t}W_{roll} \times 1m, \left[\frac{m^3}{s}\right] \tag{2}$$

For every meter length of GCL roll there is also a meter length of overlap which has an additional contribution to flow. This contribution can be calculated as follows:

$$q_{overlap} = k_{ip}\frac{h}{W_{overlap}}t \times 1m, \left[\frac{m^3}{s}\right] \tag{3}$$

Where,

$k_{ip} = in - plane\ hydraulic\ conductivity, m/s\ \ (measured\ in\ modified\ permeameter)$
$k_{cp} = cross - plane\ hydraulic\ conductivity, m/s\ (typically\ given\ as\ GCL\ specification)$
$h = hydraulic\ head\ pressure, m$
$t = hydrated\ GCL\ thickness, m\ (total)$
$W_{roll} = GCL\ roll\ width, m$
$W_{overlap} = overlapping\ width, m$

For hydraulic performance, it is clearly desirable that the flow contribution from the overlap should be negligible, i.e. $q_{overlap} << q_{roll}$. A 1% threshold is sufficient to ensure that the overlap flow contribution is less than the experimental noise generally observed in k_{cp} measurements.

The following equation is a practical way to assure that the contribution of flow from the overlap join represents less than 1% the total flow from constituent GCL rolls:

$$\frac{q_{overlap}}{q_{roll}} \leq 1\% \tag{4}$$

$$\frac{k_{ip}}{k_{cp}}\frac{t^2}{W_{roll}W_{overlap}} \leq 1\% \tag{5}$$

We can observe from Eq.(5) a few elements at play. Wider rolls offer the benefit of less overlap per square meter of GCL installed. Greater overlapping width increases the in-plane flow length thus reducing the overlap flow contribution. Increasing GCL thickness results in a reduction in calculated overlap performance because it presents a larger cross-sectional area for in-plane overlap flow and the overlap flow is compared to a thicker, better performing cross-plane flow contribution.

This method of analysis can address other design concerns highlighted by previous authors. For example, drying shrinkage or subsoil settlement can reduce the overlap width, $W_{overlap}$ (Rowe et al. 2013, Katsumi et al. 2014). In cases where drying shrinkage or differential settlement are highlighted as risks, a greater $W_{overlap}$ can be calculated and specified.

3.3 *Considerations for GCL in intimate contact with HDPE membranes*

The test configuration depicted in Figure 4a is insightful for applications where GCLs are in intimate contact with geomembranes. It has been suggested that the extrusion of bentonite into the voids of the carrier or cover geotextile will likely reduce the transmissivity value to that of bentonite itself (Koerner 2005). This transmissive interface has been carefully studied by many authors (Giroud and Bonaparte 1989, Rowe and Booker 1998). Consider the case of the nonwoven cover geotextile between an HDPE membrane and the low permeability bentonite core of the GCL. An important parameter in calculating interface flow is hydraulic transmissivity defined by:

$$\theta = k_p s \tag{6}$$

Where,

$\theta = hydraulic\ transmissivty\ of\ cover\ geotextile, m^2/s$

$s = spacing\ between\ the\ geomembrane\ and\ bentonite\ core, m$

$k_p = cover\ geotextile\ in - plane\ hydraulic\ conductivity, m/s$

Observe the importance of k_p and the effects that order of magnitude differences would have on results measured. It appears, both quantitatively and qualitatively that the bentonite does extrude into the pores of the nonwoven cover however it does not reach the hydraulic conductivity comparable to that of the bentonite core. Bentonite which extrudes into the pores of the cover geotextile has swelled more compared to the bentonite core. Furthermore, if this swelling occurs after confinement, as it did in the tests reported, then the porous fiber matrix has taken up the load and the bentonite which has swollen into the pore space is under less confinement compared to the bentonite core. Qualitative observations show the extruded bentonite tends to have a higher moisture content compared to the bentonite core of the GCL. Generally, the consistency of the extruded bentonite is like that of yogurt while the core is the consistency of peanut butter.

The results in Figure 5 suggest that direct measurement of in-plane hydraulic conductivity through the GCL is more appropriate than generalizing the cross-plane hydraulic conductivity measurement of ASTM D5887. Measurements show order of magnitude differences can exist in cross-plane and in-plane hydraulic conductivity measured in a GCL even when the special treatment of bentonite impregnation is applied to the cover geotextile.

3.4 *Implementation of the modified permeameter method*

Careful analysis of any geosynthetic should also acknowledge the reality of product variability. To deal with product variability, engineers specify manufacturing quality assurance testing (MQA) and construction quality assurance testing (CQA). In practice, index properties such as bentonite mass per unit area have proven impractical for CQA and MQA assessment of GCL overlap performance due in part to the many variables introduced during cutting, handling, sampling and transport. The modified permeameter setup could be used for quality assurance for this application. Unfortunately, the time period featured in Figure 5 is impractical for CQA and MQA purposes. The method may require a pre-hydration procedure to achieve an earlier flow rate equilibrium.

The analysis described an approximation of the actual heterogeneity of GCLs. Further analysis and testing is required to understand the stratified hydraulic conductivity of the GCL and its components. It is expected that this understanding will improve the versatility and usefulness of the model.

4 CONCLUSIONS

A standardized test method for measuring the horizontal hydraulic conductivity of GCLs was conceived and tested. The tests show that the in-plane hydraulic conductivity of the GCL can be much greater than the standard cross-plane measurement. This difference in values can have implications for GCL overlap flow calculations as well as transmissive flow within composite liner systems. It is proposed that the anisotropic nature of the GCL be recognized and tested. The anisotropic qualities of the GCL are likely due to the stratified layers of materials that make up the GCL. A deeper analysis of this heterogeneity using the modified permeameter would improve methods for the appropriate use of GCLs in containment systems.

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