A Test Method to Determine Expected GCL Porosity under Specific Site Conditions

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ABSTRACT

Determination of the porosity and void ratio of porous shrink-swell materials under conditions experienced on-site is critical to understanding expected advective and/or diffusive flux. Porosity estimates for geosynthetic clay liners (GCLs) depend on subtle interactions within the pore spaces governed by a particular leachate flux processes. For clay based lining materials, such as geosynthetic clay liners or compacted clay, the effective porosity or void ratio depends on the effective stress, saturation conditions of the lining system and the interactions between the leachate and the clay, which impact flow path tortuosity. This paper will describe a test method to calculate the porosity of GCLs under specific conditions of effective stress and saturation. The GCLs used for this analysis consisted of powdered sodium bentonite encapsulated by needle-punching between nonwoven cover and woven carrier geotextiles. Total specimen thickness was measured in a large-scale direct shear box where normal stresses were applied with step-load motors up to 1000 kPa and changes in thickness of the GCL were recorded in real-time as the GCL hydrated and consolidated. Results indicate that the total void ratio of hydrated GCLs is essentially equivalent to that of the bentonite component only, because the bentonite fills all geotextile void spaces. At stresses as high as 1000 kPa, the geotextile fibres are compressed and the geotextile voids are absent. The interparticle voids in the bentonite trend toward zero. Thus, traditional methods to measure porosity and void ratio of GCLs will over-estimate the importance of the geotextile under high confining stresses.

Keywords: GCL, porosity, void ratio, effective stress, displacement, bentonite

1 INTRODUCTION

The porosity of sodium bentonite is dependent, in part, on (i) its degree of hydration, (ii) the amount of confining stress imposed and (iii) a complex interaction of these effects. It has been well established that hydration strongly influences adjective gaseous flow GCLs, which is largely due to the porosity of the bentonite (Didier et al. 2000; Vangpasail and Bouazza 2004; Bouazza et al., 2007; Gates, 2008; Hornsey et al., 2009; Mendes et al. 2010; Rayhani et al. 2011). Likewise, the saturated GCL hydraulic conductivity has been shown to be reduced as a function of confining stress (Thiel and Criley 2005). Detailed information on the porosity and void ratio of GCLs is of particular importance when GCLs are used outside of their normal designed condition, including when employed under high confining stresses.

This paper focuses on the swelling and consolidation behaviour of a GCL subjected to different mechanical loads. Results of consolidation tests are combined with literature X-ray diffraction data to explore the interaction of clay and water particles within a GCL under applied stress conditions. The hydrated particle density of smectite, the swelling component of the bentonite, is the most difficult parameter on which to obtain an accurate measure. While it can be calculated from the position of the basal (001) reflections as measured by X-ray diffraction on orientated powder mounts equilibrated at various hydration states (Mooney et al. 1952; Chiou and Rutherford, 1997, Rutherford et al., 1997; Laird, 2006), the method requires precise knowledge of the chemistry and mineralogy of the material (Gates et al 2002; Gates, 2004; Gates et al., 2004; Likos and Wu, 2006) and is often performed under free swell conditions. In addition, GCLs are a multi-component system, so direct translation of X-ray data to GCLs is difficult.

The main focus of this study was to determine the hydrated porosity of GCLs during hydration and consolidation phases, with the goal to apply this methodology to obtain a more accurate description of the pore volume of GCLs during standard flexible-wall triaxial hydraulic conductivity tests.

2 MATERIALS AND METHODS

2.1 Geosynthetic Clay Liner

Analysis was performed to understand the evolution of the pore space of a GCL under various hydration and consolidation conditions. A sample of GCL was hydrated in tap water under 10 kPa for 48 hours, then step loaded in 32 kPa increments every 3 hours to 1000 kPa while allowing it to take up or release water. The tap water had the following characteristics: pH = 8.4; ionic strength (I) = 5.9×10^{-4} mM; electrical conductivity (EC) = 181 μS/cm; $CaCO_3$ alkalinity = 45 ppm; ratio of mono- to di-valent cations ($RMD^{1/2}$) = 0.03. The general and specific characteristics of the GCL examined in this study are summarized in Tables 1 and 2. The mass of the bentonite (M_b) was determined from the difference in mass per unit area of the GCL (M_{GCL}) and geotextile layers (M_{GT}) as outlined in ASTM D5993.

Table 1: General characteristics of GCL used in present study

GCL type	Bentonite Type	Bentonite Form	Carrier Geotextile	Cover geotextile	Bonding
X1000	Sodium	Powder	Woven Slit-Film Polypropylene	Nonwoven Polypropylene	Needle-Punched

Table 2: Specific characteristics of the GCLs used in the present study

Normal Stress	GCL Area	Initial GCL Total Mass	Initial GCL Total Thickness	Initial Geotextile Mass	Initial Geotextile Thickness	Initial Bentonite Mass
kPa	*cm²*	*g*	*mm*	*g*	*mm*	*g*
1000	464.40	285.97	8.36	18.58	3.62	267.39
Normal Stress	Initial Bentonite Moisture Content	Initial Bentonite Thickness	Final WET GCL Mass	Final WET GCL Thickness	Final DRY Mass	Final GCL Moisture Content
kPa	*%*	*mm*	*g*	*mm*	*g*	*%*
1000	8.74	4.74	426.99	4.96	264.48	66.09

2.2 Test Method

A ShearTrac-III large-scale direct shear box (Figure 1) was used. The apparatus comprises a fixed top box and a bottom box, both with internal dimensions of 305 x 500 mm. The bottom box was located inside a horizontally mobile bath, the side-walls of which extended above the base of the top box allowing complete submersion of the test sample in liquid. Loading was applied using a software-controlled micro-stepper motor connected to a worm gear and recorded via a 50 kN load cell. Displacement was recorded using a linear vertical displacement transducer (LVDT) with a 100 mm maximum travel (Figure 2). Three rigid plastic spacers were placed inside the bottom box, followed by a drilled and grooved spacer block oriented with the grooves facing up. This block ensured that the base of the GCL had free access to water during both the hydration and consolidation phases. A 215 x 215 mm sample of GCL was then cut and taped around the edges to minimize loss of bentonite during hydration and loading (Figure 3). Given the capacity of the load cell, the GCL sample was reduced in size by 50% of the standard 305 x 305 mm size to allow loads up to 1000 kPa to be recorded. The sample was placed centrally inside the top box followed by another drilled and grooved spacer, oriented with the grooves facing down, a plastic spacer and finally a solid metal platen (Figure 4). The collective weight of the three spacers on top of the GCL was taken into consideration when determining load criteria in the software. The bath was then filled to capacity with tap water and a 10 kPa constant load applied. Vertical displacement was continuously recorded in 30 second intervals during both establishment of the initial vertical load as the sample hydrated and underwent swelling, as well as during the consolidation phase. After 48 hours under 10 kPa confinement, step loading was applied to the sample in 32 kPa increments every 3 hours until a final load of 1000 kPa was achieved. A reference condition, in which the shear box was set up and operated in an identical fashion without a GCL specimen, was also performed to ensure the entire compressibility of the system could be later subtracted from the dataset.

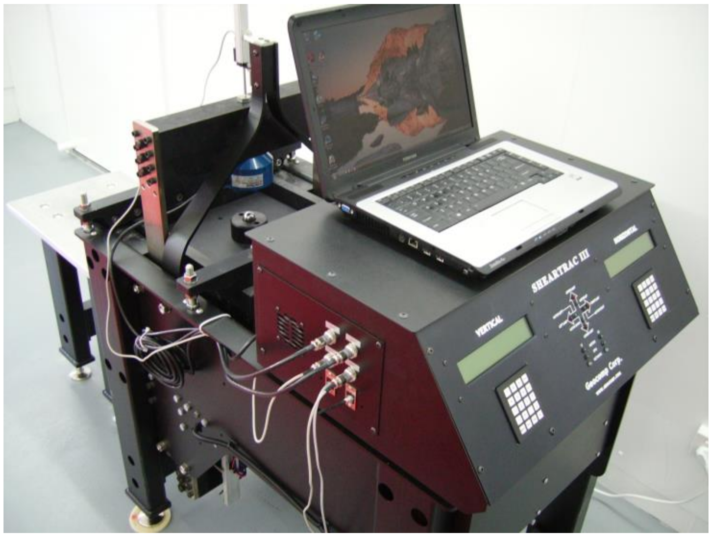

Figure 1. ShearTrac-III Large Scale Direct Shear Box

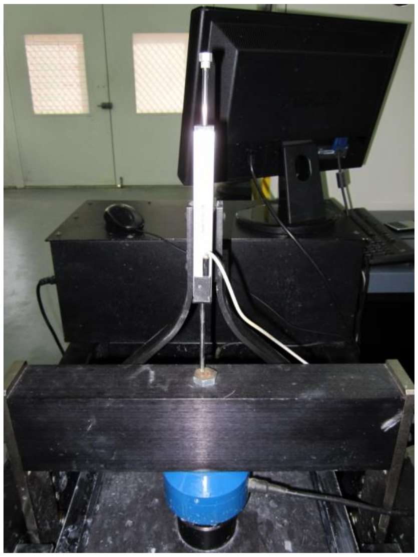

Figure 2. LVDT

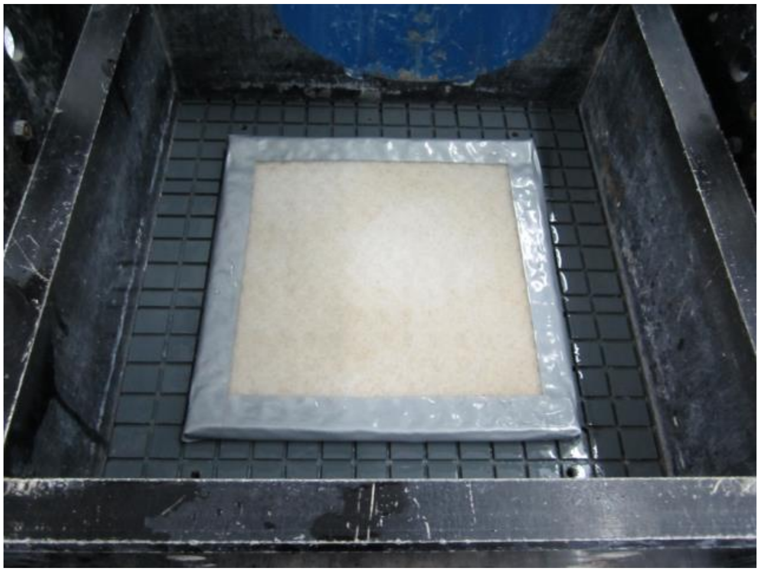

Figure 3. 215 mm x 215 mm GCL sample inside the top box

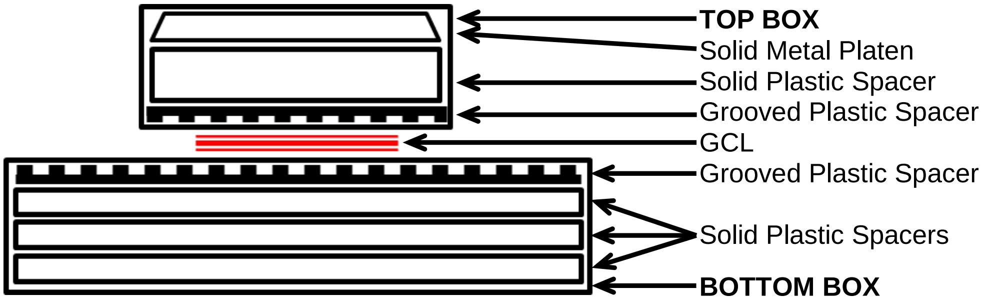

Figure 4. 1000 kPa test schematic

When the GCL sample was removed from the apparatus, final mass, hydrated bentonite thickness and moisture content measurements were taken. It was noted at this point that while a small amount of bentonite did squeeze into the tape, no bentonite was lost from the edges of the sample. Hydrated bentonite did extrude, however, through the top nonwoven layer into the open channels of the grooved spacer on top of the GCL (Figure 5). This photo also shows the extent of bentonite intrusion into the top nonwoven layer.

Figure 5. Hydrated bentonite extruded into the grooves of the spacer block after application of 1000kPa

2.3 General Relations

Both porosity and void ratio are considered state variables important in assessing the hydraulic performance of geomaterials, including GCLs. Current literature is contradictory regarding the values of void ratios returned for GCLs under hydrated condition, with values as high as 3.5 (Petrov and Rowe 1997; Abuel-Naga et al. 2013). In some cases, such high void ratios may be a direct result of GCL thickness determination before loading rather than after load has been removed. It has been observed herein that the thickness of the GCL under load is approximately equal to the thickness of the bentonite component when measured after load has been removed. Such a result implies that the geotextile component of a GCL imparts only a minor fraction to the GCL's porosity when hydrated under most confining conditions. In such a case, the void ratio of the bentonite would then be largely responsible for the hydraulic performance of the GCL, a supposition that has been considered elsewhere (Sattar and Gates, 2009).

General volumetric and gravimetric relations were used to fully characterize the samples. The sample void ratio was calculated from displacement using an extension of the concepts developed by Likos and Lu (2006) for compacted bentonites. Likos and Lu (2006) separated the bentonite void ratio into additive terms related to interlayer and interparticle pore components and a similar treatment can be performed on GCLs. For a GCL, the total GCL void ratio (e_{GCL}) is an additive function of the void ratios of the bentonite

(e_B) and the geotextiles (e_G):

(1)

or

(2)

where e_{Bil} and e_{Bip} are the interlayer and interparticle contributions. In our method,

1) the hydrated (ρ_{hyd}) density of the bentonite component was estimated based on polynomial expressions fitting measured XRD d-values from water adsorption isotherms (Chiou and Rutherford 1997).
2) e_{Bil} was estimated from the hydrated (ρ_{hyd}) and particle (ρ_b) density of the bentonite component.
3) e_{Bip} was estimated from the calculated density of the GCL, which itself was estimated from the masses and densities of the various components, including the bentonite (ρ_{hyd}) the geotextiles (ρ_G) and water (taken as 0.9974 g/cm^3).
4) e_{Bil} was estimated from the volume of bentonite (M_b/ρ_{hyd}) (M_B is the hydrated mass of bentonite) and solids volume and also from the additive relation of Likos and Lu (2006).
5) e_G was estimated likewise estimated from M_G/ρ_G, with M_G the mass of geotextiles and ρ_G the density.

3 RESULTS AND DISCUSSION

The evolution of the vertical displacement of the GCL sample while initially loaded under 10 kPa during the hydration phase and then throughout the consolidation phase up to a final confining stress of 1000 kPa is depicted in Figure 6. It is apparent that after 48 hours under 10 kPa, the sample was still hydrating and swelling. As is well known (Mesri and Olsen, 1971; Petrov et al. 1997; Shackelford et al. 2000), hydration under higher confining stresses can attain equilibrium much quicker.

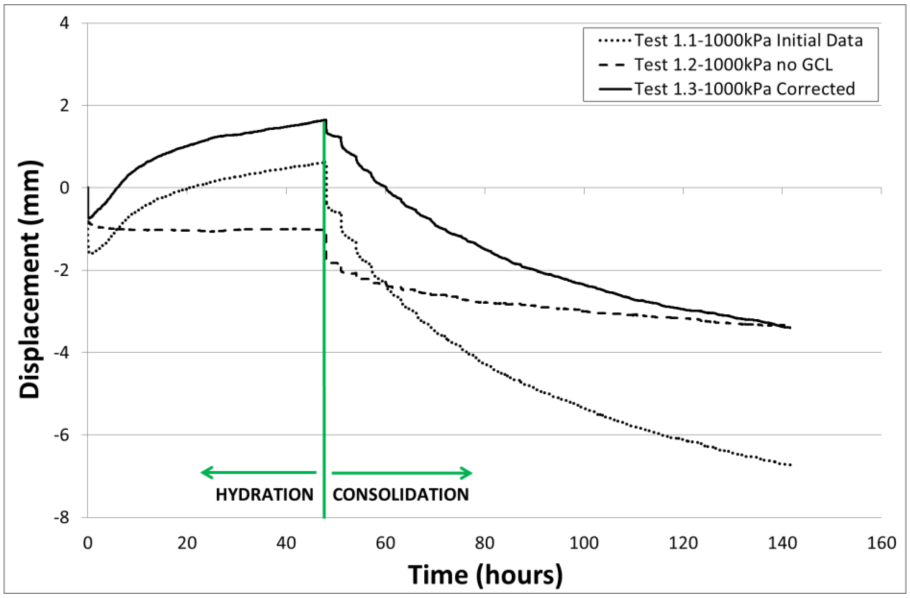

Figure 6. Evolution of displacement during hydration and consolidation phases

Figure 7a shows the partitioning of void ratio between the two main components of the GCL. Under low confining stress (10 kPa), the hydrated GCL void ratio is largely shared by both e_B and e_G. Values of e_G

become insignificant rapidly with bentonite swelling, which displaces air and water from the geotexiles. This process was largely concluded by 48 hrs. Thus even under conditions of very low loadings and still incomplete hydration, the porosity of the geotextile component may be negligible after 2 days hydration. The veracity of this result will be bentonite dependent, as some bentonites may hydrate at a lower rate (Vangpasal and Bouassa, 2004; Bouazza et al, 2007) or have lower swellability (Gates, 2007; Hornsey et al., 2009), thereby being less effective at filling all the geotextile void space.

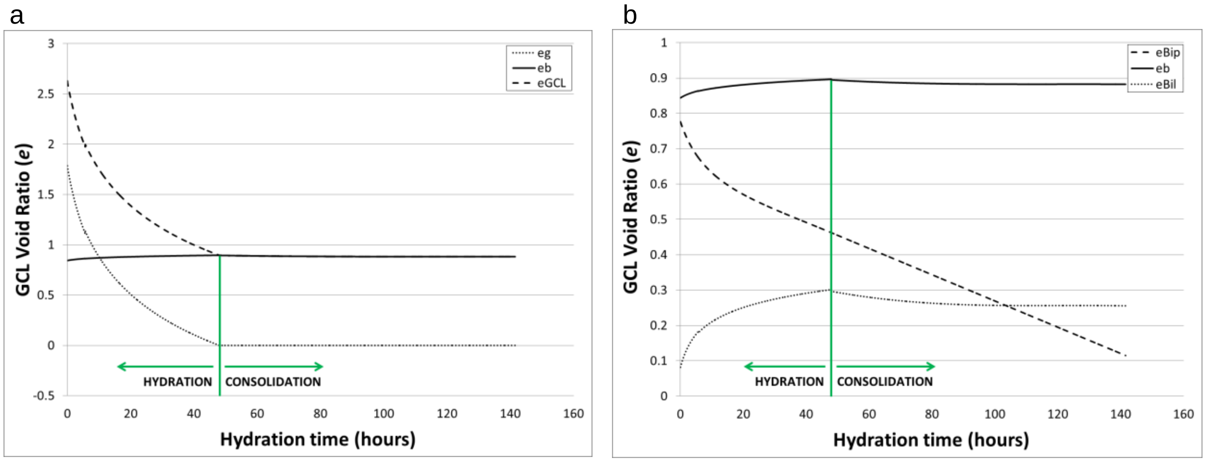

Figure 7. Evolution of void ratios of GCL (a) and Bentonite (b) components

The evolution of e_B, as separated into interlayer and interparticle components is shown in Figure 7b. The interparticle void ratio of the bentonite decreased throughout the experiment by 85%, while the interlayer void ratio increases during the first 48 hours of hydration, then decreases with increased loading. Half of the initial drop in e_{Bip} was due mostly to hydration and swelling of the bentonite during the hydration stage, whereas the remaining loss of interparticle voids occurred during consolidation under the increased loads. Thus, the active void ratio of hydrated GCLs under such conditions can be expected to be essentially only that of the interlayer, e_{Bil}. Under these situations, the bentonite void ratio can be grossly overestimated if its determination is made based on GCL thickness after loads have been released. For void ratio determinations of hydrated sodium bentonite under typical 35 kPa conditions used in saturated hydraulic conductivity tests, we suggest using a hydrated bentonite density of 1.5 g/cm^3.

When porosity and void ratio can be determined and the specific gravity, ρ_f, and viscosity, η_f, of the fluid, f, are known, it has been shown by Sattar and Gates (2009) that the saturated hydraulic conductivity of a fluid (k_f) through a bentonite can be estimated from the expression:

$$/\eta \qquad (3)$$

Where ε is the bentonite porosity and r_f is the diameter of fluid filled pores. k_f is thus largely dependent on knowledge of changes in the porosity and pore diameter (Kemper and Evans, 1963). With measured saturated hydraulic conductivity, for example with a flexible walled triaxial permeameter under similar hydration and confining conditions, the effective pore diameter can thus be estimated.

In saturated and compacted GCLs, typical pore diameters are tens of nm (Bourg et al., 2006), and the water in these pores should be largely considered bound water (Gates et al, 2012); therefore, most water transport is dependent on diffusion. Because pores are discontinuous in bentonites, and the liquid phase is only a small portion of the total volume (and it is tightly bound), the effective diffusion coefficient D_p, is generally less than diffusion of bulk water (D_o) and can be estimated from:

(3)

where θ is the volumetric water content and ξ is the tortuosity factor. D_o is generally taken as (2.3×10^{-9} m^2/s). The closer ξ is to unity, the less tortuous the flow path is through interconnected pores. The tortuosity is obviously dependent on the geometric configuration of the pores, their interconnectivity and size. Measured diffusion rates under similar hydration and confining conditions can thus allow assessment of the tortuosity of the GCL.

4 CONCLUSIONS

For a GCL that becomes fully hydrated while subjected to a confining stress, the total void ratio is essentially equivalent to that of the bentonite component only, because the void spaces of the geotextile component become occupied with hydrated bentonite. The hydrated and confined bentonite void ratio itself can be considered to be essentially made up predominantly of the interlayer pores, which contain strongly bound water. Under high confining stresses, the interparticle pore water, which is held less strongly at clay surfaces, is negligible. Thus, traditional methods to measure porosity and void ratio of GCLs will over-estimate the importance of the geotextile under high confining stresses. In this regard a hydrated particle density of ~1.5 g/cm^{3}should be used for fully hydrated GCLs under 35 kPa applied stress, as in typical hydraulic conductivity testing.

5 ACKNOLEDGEMENTS

The authors are grateful for the assistance of Mr J Buckley and Mr Warren Hornsey during early stages of this research, and for continued support provided by Mr Richard Austin at Geofabrics Australasia.

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